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Design and Testing of the WVU Challenge X Competition Hybrid Diesel Electric Vehicle

Howard Andrew Mearns

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Mechanical Engineering

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Abstract

Design and Testing of the WVU Challenge X Competition Hybrid Diesel Electric Vehicle

Howard Andrew Mearns

The WVU Challenge X Team was tasked with improving the fuel economy of a 2005 Chevrolet Equinox while maintaining the stock performance of the vehicle. A through-the-road-parallel hybrid diesel-electric was implemented to accomplish this goal. The greatest potential for improvement to hybrid electric vehicle technology is in energy storage in terms of cost, size, lifespan, and efficiency. Currently, battery cost is limited by the expense of the base materials. The characteristically low power density of electrochemical energy storage rather than energy density is responsible for the size of current hybrid energy storage systems. A limited lifespan is inherent in electrochemical energy storage. The WVU Challenge X Team sought to produce a hybrid electric vehicle with a high power, efficient energy storage system with an extended lifespan and costs not limited by the base materials used in manufacture. The team selected an ultracapacitor pack with an effective energy storage of 0.17 kWh to accomplish those goals. The work presented analyzed this energy storage system, the powertrain architecture associated with it, and the unique control strategy developed to control it. The fuel economy of the stock vehicle was compared with the diesel powertrain only as well as the complete hybrid electric powertrain selected by the team. Road load was calculated over the course of the competition drive cycle and was compared to the power capability for the electric motors. The cycle energy and power were calculated for each braking and power event and the statistics compared with the capabilities of the energy storage system, hybrid electric system, and the actual performance during the 2007 Challenge X competition. The small effect of a 20% reduction in the size of the selected energy storage system and its efficiency were also discussed. Finally, suggestions for improvement to the architecture, design and control strategy were discussed.

Dedication

I dedicate this work to my father who instilled in me the importance of education and supported my first steps toward engineering.

Acknowledgements

I would like to thank my wife, Brooke, for all of the patience and support over the years.

I would also like to thank Afshin, Dr. Nutter, and Dr. Klink for the random solicited help in solving some of the more challenging technical hurdles of this project.

To all the members of the WVU Challenge X Team, especially, Colin Hultengren, Derek Johnson, Jeremy Sigley, George Titchnell, and Paul Beidler; thank you for your dedication, without which this work would not have been possible.

I would lastly like to thank my advisor, Dr. Clark, for his support over the years of my extended stay here in the department.

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Nomenclature

ANL	Argonne National Laboratory
ESS	Energy Storage System
MPG	General Motors' Michigan Proving Grounds
mpg	Miles per Gallon
SOC	State of Charge of the Energy Storage System
SOC_t	Theoretical or Desired State of Charge calculated using the vehicle speed
SOC_a	Actual State of Charge as computed using the ESS Voltage
SUV	Sport Utility Vehicle
UC	Ultracapacitor
APP	Accelerator Pedal Position
CAN	Controller Area Network-High Speed Serial Communication Protocol
GMLAN	General Motors' CAN protocol and messaging system
RL	Road Load

Introduction

While there is much debate over the actual lifespan of the world's oil supply, Figure 1 shows the Hubbert projection of worldwide production of oil using conventional production technology.

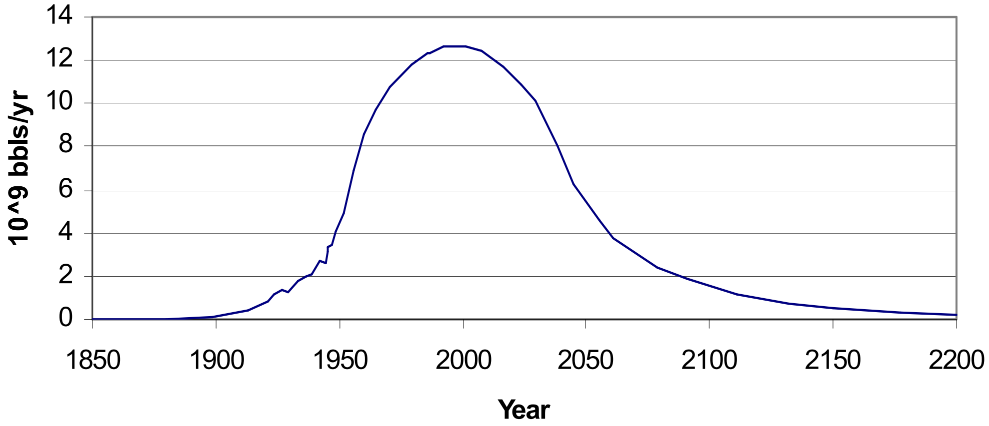


Figure 1: Hubbert Oil Production Estimation [1]

Users of oil are not likely to reduce their energy use in a corresponding manner. World population since the inception of widespread oil usage has risen dramatically as shown in Figure 2. The increase in demand will be even greater than population change indicates, as many countries are only now joining the industrial age.

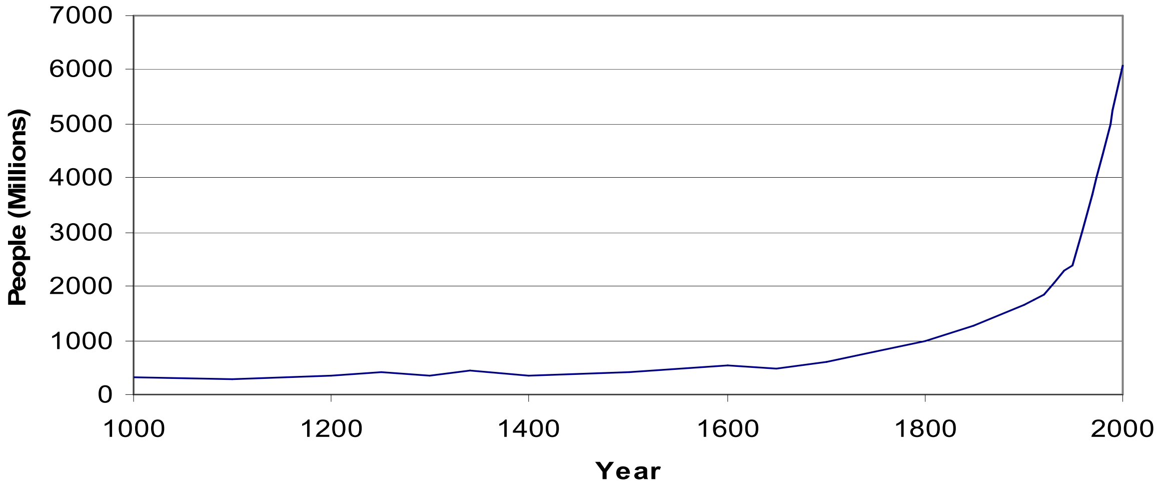


Figure 2: World Population Growth [4]

Figure 3 shows the average monthly price of oil and the inflation adjusted values for the same time period. The cost of crude oil has recently exceeded levels reached during the oil embargoes of the 1970's.

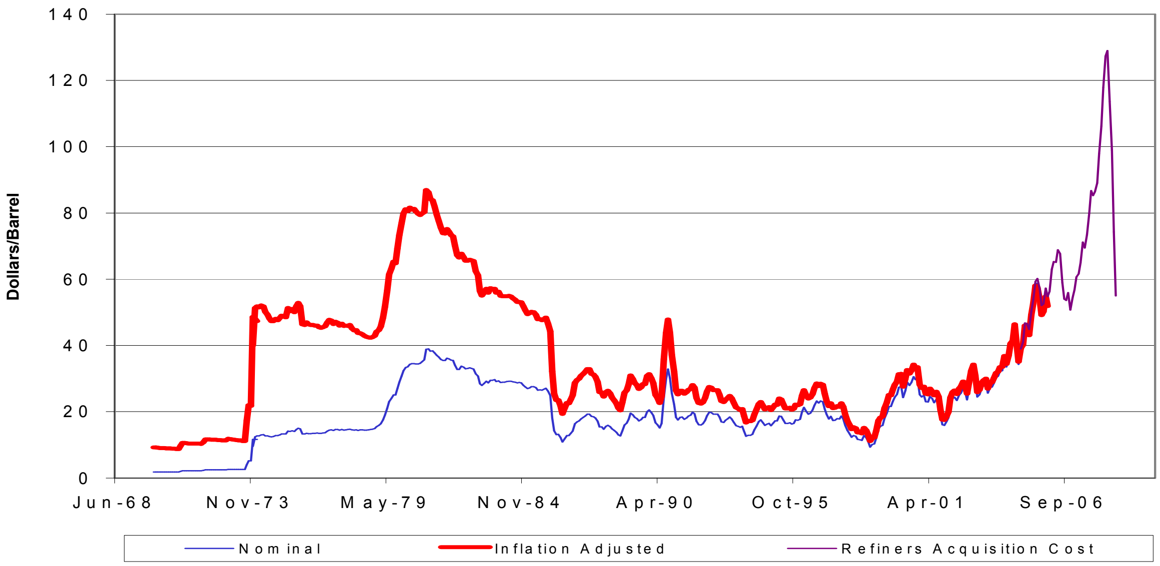


Figure 3: The Price of Crude Oil [2, 3]

These costs will continue to rise as more complex and expensive methods of drilling and extraction are employed to meet world demand.

The cost of oil affects consumers most prominently in transportation costs. Figure 4 shows typical drivetrain losses which total to more than 75% for a passenger vehicle. Note that by far, the largest loss is with energy conversion in the engine itself at greater than 60%. This makes it the largest target for improvement.

There are only two ways to avoid the continuing increase in demand for petroleum. Petroleum use can be displaced directly through the use of alternative fuels such as ethanol and biodiesel and indirectly with electricity and hydrogen by storing energy from stationary sources, such as wind, solar, and hydroelectric energy. Currently, there are obstacles for each of those energy sources to overcome. Petroleum use can also be reduced by increasing the energy efficiency of vehicles.

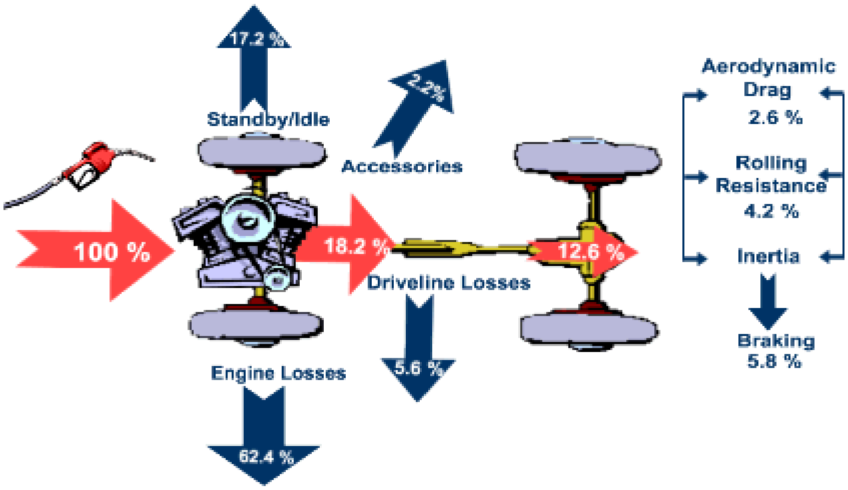


Figure 4: Drivetrain losses, from [33].

A hybrid vehicle is a vehicle that converts more than one form of energy to mechanical work for propulsion. The technologies are discussed in the literature review. Usually, one part of the propulsion system converts a fuel into mechanical work and a second system collects excess energy from this process and the vehicle itself to store and later reuse. This usually reduces the fuel consumed by the primary producer of mechanical work but could also be used to increase the total output of the vehicle without a reduction in fuel economy.

Since energy will be an increasingly expensive commodity for consumers, conservation on the part of the consumer will become more fiscally beneficial in the future. Over 360,000 hybrid vehicles were sold in the US in 2007, up from less than 20,000 in 2000 [34]. Hybrid vehicles are gaining popularity and market share in part due to fuel prices and a desire by many to decrease their effect on the environment.

Hybrid vehicles are moving from a novelty into refinement and standardization. A hybrid by definition is more complex and has more parts. Additionally, these extra parts are not yet standard parts in the automotive industry and are relatively expensive to produce, such as high efficiency electric motors, electric motor controllers and high efficiency batteries.

So, a hybrid vehicle will likely cost more than a comparable conventional vehicle, though an increase in market share and advances in technology are reducing these added costs.

The most obvious need for improvement in hybrid technology is in the energy storage media. Currently, nickel-metal-hydride batteries are the most common. The cost and reliability of current energy storage media are holding back the depth and breadth of the hybrid market. The cost of the energy storage system (ESS) is a large portion of the hybrid premium because of the basic materials and processes used to manufacture them.

Increasing the power density and efficiency of storage media reduces the overall size of hybrid packages, reducing the cost and weight of hybrid vehicles. The industry is now focusing on more reliable and less expensive energy storage with increased storage efficiency.

"BAE Systems' new lithium-ion energy storage system is lighter than energy storage systems currently in production. Reducing vehicle weight improves fuel economy and reduces emissions. The new energy storage system also is more efficient and lasts longer than the leading alternatives in use today."[10] This announcement is significant because of the move to a better technology in terms of weight and efficiency, but also because it is a departure from BAE Systems' long standing use of lead acid batteries. The switch makes the value of the improvement in weight, cost and performance from this technology apparent.

Toyota has announced that they will step up efforts to produce lithium-ion hybrid batteries, which they say are necessary to cut the current hybrid cost premium in half [8]. As a longstanding leader in hybrid technology, Toyota's desire points to the necessity for better energy storage. As for other industry efforts towards improved storage, Johnson Controls completed a $4 million laboratory to develop lithium ion batteries for hybrid vehicles in 2005. [9]

Commercially, there is an obvious economic desire to increase the density and reduce the cost of the energy storage systems on hybrid vehicles. Less economic benefit is available for alternative fuels on a consumer level; however current conventional fuel costs are starting to change that reality.

In light of the foreseeable increase in petroleum price and usage as well as the plausible future decline in petroleum production, the US Department of Energy, Argonne National Laboratory (ANL), and General Motors sponsored the Challenge X competition. The Challenge X project at WVU was governed by the rules of the Challenge X competition organizers. The competition consisted of 17 schools from across the United States and Canada including WVU that took on the same challenge. The overarching theme of the competition was sustainable mobility, while the goals of the competition were to reduce emissions and increase fuel economy while maintaining performance and consumer acceptability.

The basic design concept for WVU Equinox Conversion was conceived in 2004 by the team as the design phase of the competition began. The team selected a diesel engine as its primary power source. This allowed an immediate gain in fuel efficiency with respect to the stock engine. An automatic transmission was selected as a reflection of the desire of the majority of consumers and of the experience of the university with previous vehicle competitions. The team also selected an electric hybrid system to further increase vehicle efficiency by storing braking energy to later be reused for propulsion in order to displace fuel. The short, high power nature of braking events led to the need for an efficient, high power storage media. Energy storage was therefore sacrificed for energy efficiency and ultracapacitors were chosen to store the recaptured braking energy.

Objective

The objective was to examine the selection and design of the hybrid electric system and control strategy of the WVU Challenge X Equinox SUV, analyze this vehicle’s performance and propose architecture and control strategy changes that could have benefited the effectiveness of the hybrid drivetrain.

The hybrid electric system and control strategy were analyzed by comparing the fuel economy performance of the WVU Challenge X 2005 Equinox conversion with a stock Equinox. The WVU Equinox had a diesel hybrid electric powertrain.

The advantage of possible changes in architecture were analyzed using data collected and processed to show the effectiveness of the current system in collecting and using energy and the energy that could have potentially been collected.

Participation on Challenge X Team

The design and concepts implemented in this vehicle were chosen by the WVU challenge X Team. The author played a major role in all of the group discussions and performed research for the team on possible components to be used. These discussions included both physical architecture philosophy and the control theory for the components selected. In year one of the competition, the team did extensive computer simulation of the proposed designs. The author served as support for the teams modeling efforts by reviewing component models, assisting in debugging the team’s models as well as the simulation software used by the team. After the vehicle’s architecture was complete and components were selected, the team began building the vehicle in 2005. The author assisted in designing and fabricating many parts used to integrate the new components in the vehicle as well as teaching many team members to use the tools available to fabricate those components.

Literature Review

Conventional vehicles waste energy associated with the momentum of the vehicle as heat when brakes are applied. Conventional gasoline powered vehicles waste energy through throttling losses. The efficiency of producing power is reduced as less power is requested. The engine wastes significant energy when idling since the vehicle does not require propulsive power from it. The transmission in a conventional vehicle is also inefficient. There can be large losses in the transmission itself and it can prevent the engine from operating at its most efficient speed.

Hybrid Concept

The average passenger vehicle needs between 10 and 30 hp to maintain highway speeds on level terrain. For example, at 70 mph, the WVU Equinox requires 26 hp to maintain speed. The surplus of power available in most vehicles is for intermittent use in acceleration and hill climb and is exacerbated by increased loads while towing. The surplus power is also available in part to satisfy customer performance expectations. These periods of operation are also the most detrimental to distance specific fuel economy for the vehicle.

Series Hybrid

A series hybrid vehicle uses a prime mover, a device for converting energy stored in a fuel, to generate energy that is stored and then used in the propulsion of the vehicle. The prime mover/generator can either be load-following or load-leveling. The load-leveling hybrid has a smaller prime mover sized to generate the average power required by the vehicle. The load following hybrid has a larger prime mover sized to handle the average power demands plus some portion of the peak demands of the vehicle. The load following hybrid has a smaller energy storage system than the load-leveling hybrid. The balance between these two concepts depends on the use of the vehicle and weight, cost, and efficiency of the components. This type of hybrid system is usually limited by the efficiency of transfer and storage of the energy. In the series electric system, the efficiency of the two motors, controllers, and the energy storage system are not insignificant and can reduce the advantages of this type.

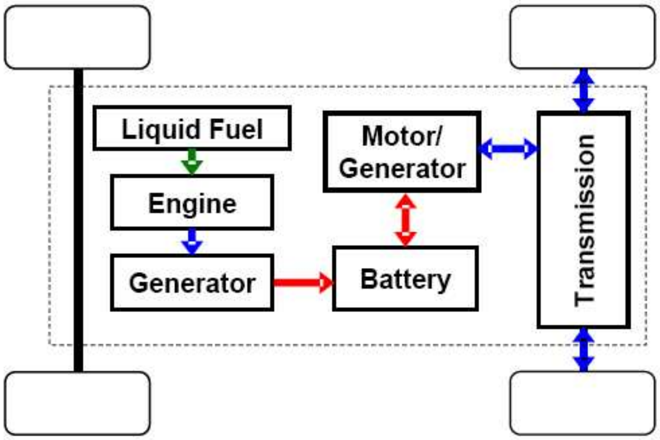


Figure 5: Series Hybrid Architecture from, [25]

Parallel Hybrid

The parallel hybrid uses a prime mover and a secondary propulsion system in parallel. Both systems apply power to the road mechanically. The secondary propulsion system can be integrated into a conventional powertrain by providing power in parallel with the engine at the transmission input, called a pre-transmission parallel, or supply power to the road more directly after the transmission, called a post transmission parallel. Further, in the post transmission parallel, the secondary propulsion system can be mechanically tied to the same driveline as the prime mover or can have a completely separate mechanical path to the road, known as a through-the-road-parallel hybrid. Both types of parallel hybrids have disadvantages that affect the system effectiveness in different ways.

The use of a pre-transmission parallel system allows the hybrid system to operate efficiently over a larger portion of the vehicle's operating range. It will also reduce weight and cost savings if it doubles as the starter and alternator. The Honda Insight as well as the Saturn Vue and Chevrolet Malibu are of this design. The Insight has a medium hybrid system with the motor mounted on the flywheel of the engine where the Vue and Malibu have belt driven alternator starter design and are milder hybrid vehicles comparatively.

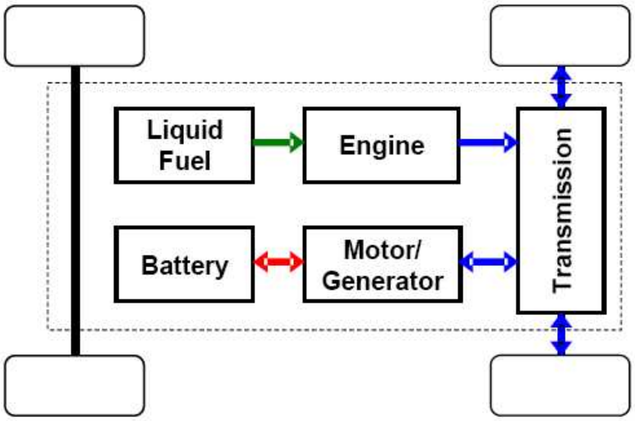


Figure 6: Parallel Hybrid Architecture from, [25]

The use of a post transmission parallel system avoids the losses associated with power flow through the transmission, but the fixed gearing reduces the efficiency of the system at low speed.

Series-parallel Hybrid

This type consists of a motor on either side of a transmission such that power can either flow mechanically from the prime mover to the road (parallel with the electric motors), or from the prime mover to the first motor, electrically to the second and then to the road mechanically (as in a series hybrid). Some advantage can be obtained over one of the previously discussed types with a conventional automatic transmission or what might be called a pre/post parallel transmission hybrid. The true advantage, however, is in using these two motors to simplify the design of the transmission itself, thus saving parts, cost, weight and space. Mechanically, one of the simplest designs of this type can be found in the Toyota Prius [26]. A cross section of the Toyota Hybrid System powertrain is shown in Figure 7. Note the lack of virtually any conventional transmission components. Here the engine, motor and final drive are each attached to one member of a planetary gear system with a second motor in parallel with the final drive. Even this simple drivetrain allows the vehicle to save fuel using several hybrid strategies. It can use regenerative braking to capture otherwise lost energy. Fuel can be saved by stopping the engine when it would normally be idling as well as when the vehicle is capable of electric only operation. While none of these functions are unique to this specific architecture or a series-parallel hybrid in general, it is impressive for such a mechanically simple powertrain to have so many benefits. The motor associated with the engine can capture excess energy resulting from the engine operating at a higher, more efficient power level. Finally, the Electric CVT that this drivetrain forms has two efficiency benefits; operation of the engine at optimal speed for required torque and its own relatively efficient transmission of power.

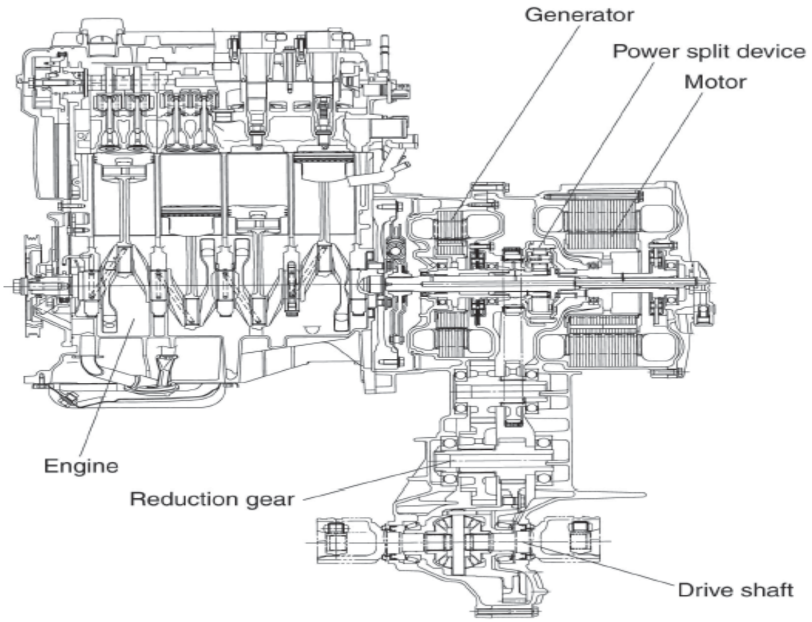


Figure 7: Prius Hybrid Powertrain, from [26]

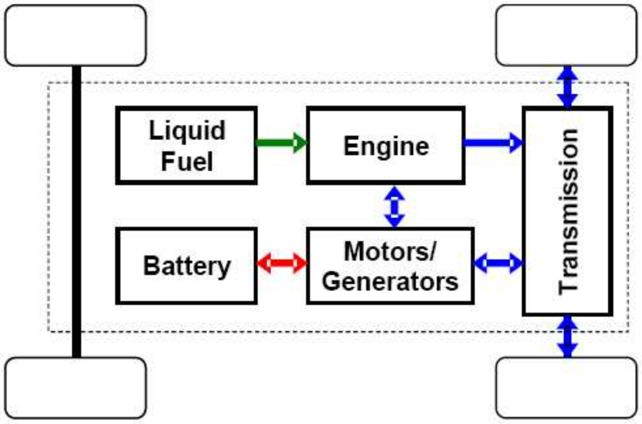


Figure 8: Series-Parallel Hybrid Architecture, from [25]

Figure 8 shows the power flow within a series-parallel hybrid powertrain. The motors/generators are frequently integrated within the transmission or its housing.

Depth of Hybridization

Though the above are the broadest classes of hybrids, there is a myriad of architectures all of which are not easily placed within the above categories. Further, the degree of hybridization can also be classified by the capabilities of the system.

A start-stop hybrid can be limited to stopping the engine when it would normally be in an idle condition and starting it again when the user demands more power. This type of hybrid system will also power vehicle accessories while the engine is shut off. It can replace the starter and alternator of the vehicle.

Make	Model	Comments	City mpg	Hwy mpg
Sedans:				
Toyota	Prius	Power Split	48	45
Honda	Civic	Full-hybrid system	40	45
Nissan	Altima Hybrid	Similar to Toyota	35	33
Toyota	Camry Hybrid	10 mpg better than V6	33	34
Chevrolet	Malibu Hybrid	Start Stop	24	32
Lexus	GS 450H		22	25
Lexus	LS 600 L		20	22
SUVs:				
Ford	Escape Hybrid FWD	Most Fuel Efficient SUV	34	30
Ford	Escape Hybrid 4WD	Most Fuel Efficient SUV	29	27
Saturn	Vue Green Line	Start Stop	25	32
Toyota	Highlander Hybrid 4WD	Power Split	27	25
Chevrolet	Tahoe Hybrid 2WD	2-Mode	21	22
Chevrolet	Tahoe Hybrid 4WD	2-Mode	20	20
Lexus	RX 400h 2WD		27	24
Lexus	RX 400h 4WD		26	24

Table 1: 2008 EPA Fuel Economy for Hybrid Electric Passenger Vehicles in Production [27]

A mild hybrid would focus on capturing regenerative braking and assisting the vehicle’s primary propulsion system, but the hybrid system would not be powerful enough to power the vehicle by itself. It may or may not include the start-stop function described above.

A full hybrid will function as a mild hybrid would; however, it would have the capability to power the vehicle by itself depending on conditions such as speed and driver demand.

Table 1 lists the hybrid vehicles produced for the US market. Note that none is solely series hybrid. These vehicles range from stop-start mini hybrid systems to full hybrids taking advantage of most of the fuel economy advantages possible with a hybrid system.

Technologies

Though all currently available hybrid passenger vehicles use an electric hybrid system with an electrochemical storage system, both fluid and mechanical storage systems are theoretically possible and have been researched.

A hydraulic hybrid uses an incompressible fluid in conjunction with a compressible fluid in an accumulator to store energy as with any hybrid and theoretically in any fashion capable with an electric hybrid system. Several heavy-duty vehicles have been produced with parallel and series hydraulic hybrid systems as well as prototype passenger vehicles [30]. The series vehicles are full hybrids while the parallel types are used for launch assist. This hybrid technology was not selected because the energy storage density was calculated to be relatively low.

In place of electrochemical storage it is also theoretically possible to store energy kinetically in an ultra high-speed flywheel driven by an electric motor. This type of storage medium has been developed and can be enclosed in a vacuum container to avoid frictional losses and operate at high speeds using magnetic bearings and composites for the flywheel materials. However, a technology demonstrator was built using low speed bearings and a steel flywheel without a vacuum container [11].

Equinox Conversion

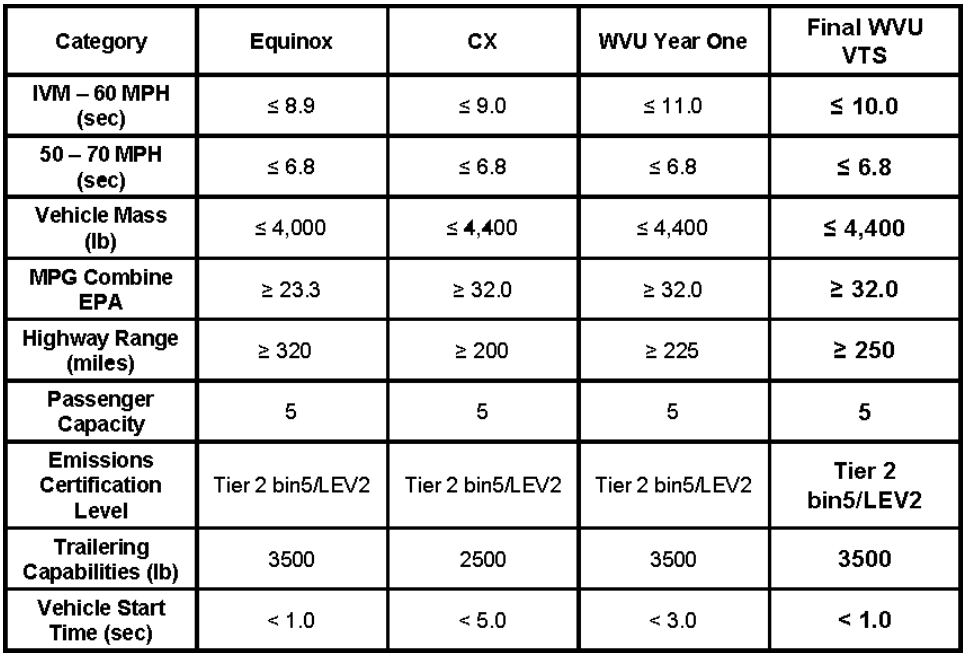
Competition Challenges

The competition used a stock 2005 Chevrolet Equinox as a base platform. The organizers challenged the team to build a vehicle that maintained the performance of the stock vehicle while reducing emissions and increasing fuel economy. The vehicles were then tested for acceleration times in the 0 to 60mph and 50 to 70mph speed ranges. The fuel economy was tested in an extended prescribed on-road course and a shorter course was used to test emissions on-road. The all wheel drive capabilities of the vehicle were tested on a timed acceleration test on a reduced traction surface. The vehicle was also required to accelerate up a prescribed grade to test the ability of the vehicle to tow additional cargo.

Initial Design Concepts

The first year one goal set by the organizers was determining the technical specifications of the vehicle. The stock vehicle and competition goals were given and then the team decided on separate goals and whether to relax or exceed the stock and competition specifications.

With the specifications presented in Table 2 in mind, the WVU Challenge X Team chose to use a diesel engine to avoid throttling losses and allow the use of B-20 Biodiesel fuel to reduce emissions and a post transmission ultracapacitor hybrid system to maximize the braking energy stored. Both of these hybrid choices minimized the losses associated with recapturing the momentum of the vehicle: the post transmission architecture avoided as many drive train losses as possible and the ultracapacitor storage system substantially increased the efficiency of the energy storage when compared to batteries.



Category	Equinox	CX	WVU Year One	Final WVU VTS
IVM – 60 MPH (sec)	≤ 8.9	≤ 9.0	≤ 11.0	**≤ 10.0**
50 – 70 MPH (sec)	≤ 6.8	≤ 6.8	≤ 6.8	**≤ 6.8**
Vehicle Mass (lb)	≤ 4,000	≤ 4,400	≤ 4,400	**≤ 4,400**
MPG Combine EPA	≥ 23.3	≥ 32.0	≥ 32.0	**≥ 32.0**
Highway Range (miles)	≥ 320	≥ 200	≥ 225	**≥ 250**
Passenger Capacity	5	5	5	**5**
Emissions Certification Level	Tier 2 bin5/LEV2	Tier 2 bin5/LEV2	Tier 2 bin5/LEV2	**Tier 2 bin5/LEV2**
Trailering Capabilities (lb)	3500	2500	3500	**3500**
Vehicle Start Time (sec)	< 1.0	< 5.0	< 3.0	**< 1.0**

Table 2: Vehicle Technical Specifications

Selection of Motors and Energy Storage

Through the use of PSAT Modeling and by considering the limitations of packaging constraints and the hardware available commercially, the team selected two 15 kW peak permanent magnet low speed wheel motors from PML-Flightlink Ltd. The physical vehicle architecture lent itself to a through the road parallel system, so the conventional powertrain was placed in the engine compartment, while the hybrid propulsion motors were attached to the rear wheels. To store the energy recaptured by these motors, the team chose to use 115 ultracapacitors at 2700 farads each arranged in 5 parallel strings of 23 cells in series. This arrangement allowed the team to store effectively about 0.5 megajoules of energy which allowed the vehicle to store a 15 second braking event or power the motors and the vehicle for a similar period of time. Ultracapacitors were chosen instead of batteries for the following reasons: high power density, high efficiency and significantly longer cycle lives.

The WVU hybrid system added approximately 400 lbs. to the 4000 lb. stock vehicle. This ratio of the added hybrid system weight to stock vehicle weight limited the size of the hybrid system and consequently limited the effectiveness of the hybrid system through the capacity of the energy storage system and the power of the electric machines.

Comparison of Energy Storage Media Performance and Specifications

Cost and added weight are the biggest detractors from hybrid systems. The added weight is counter to the goal of a hybrid system since the added weight requires more energy to accelerate with the vehicle and overcome the added tire rolling resistance. The volume of the system is also a consideration but only to the point of integrating the system or requiring the vehicle platform to be enlarged. The energy storage capacity of a hybrid system depends on the type of hybrid system, the mass and the mission profile of the vehicle.

The power required from the ESS depends on the capability of the hybrid system to recapture the energy of the vehicle. The rate of capture is either be limited by the practical size of the ESS or the hybrid motors. The density of the ESS in relation to the power and energy above limits the size of the ESS.

Traditionally, the ESS components have an excess of energy density and are limited by power density. This is further aggravated by charging limitations lower than the discharge rates. The primary benefit of the hybrid system is the capture of kinetic energy that must be captured quickly during braking. Currently, all hybrid passenger cars use Nickel-metal Hydride batteries. The Office of Vehicle Technologies within the Department of Energy is responsible for energy storage research and development in support of the President’s Advanced Energy Initiative of 2006. This work is focused on the development of two technologies for both HEV and PHEV energy storage: Lithium based battery chemistries and Ultracapacitors [28]. Ideally, the ESS for a hybrid vehicle has both significant energy and power density. If short-term event level energy capture and use is the goal of the hybrid system, power density is far more important. Further, short-term power density is the goal and not sustained power.

The motor power from the WVU equinox and the energy from the largest energy event during the 2007 competition was used as a ratio between energy and power density. The black line in Figure 9 and Figure 10 shows the density ratio and the lack of ESS components ideally suited for hybrid systems. The trend of energy storage improvements seemed to be in greater densities of energy or power but not both [12-23].

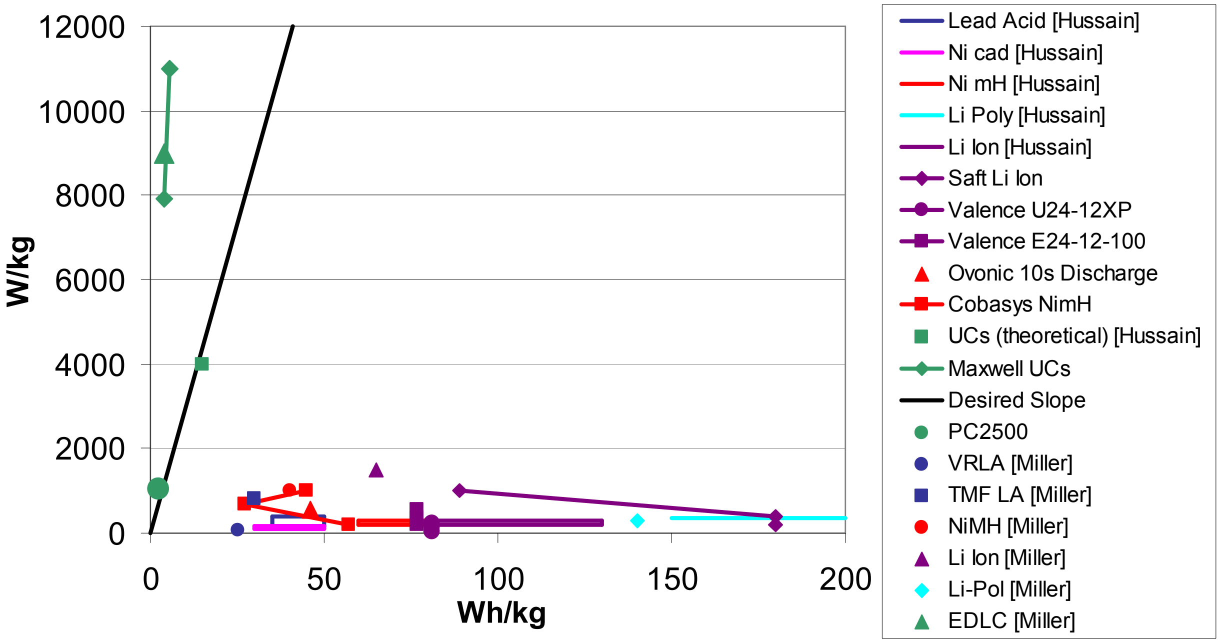


Figure 9: Energy and Power Density of Hybrid Energy Storage Technologies [12-23]

Note that the WVU Equinox UCs had the same power density as some new lithium and Nickel metal hydride battery specifications, however, these were not available when the team selected ESS components. Part of the apparent advancements in power density were a result of specifications for peak power. The higher power densities shown were thirty and even ten second peak power rates, based on the length of typical events in a hybrid system. These specifications were either in recognition of the requirements for their intended use or of improvements necessary to meet these specifications. UCs also have increased in power density, but not energy density as is theoretically possible [12].

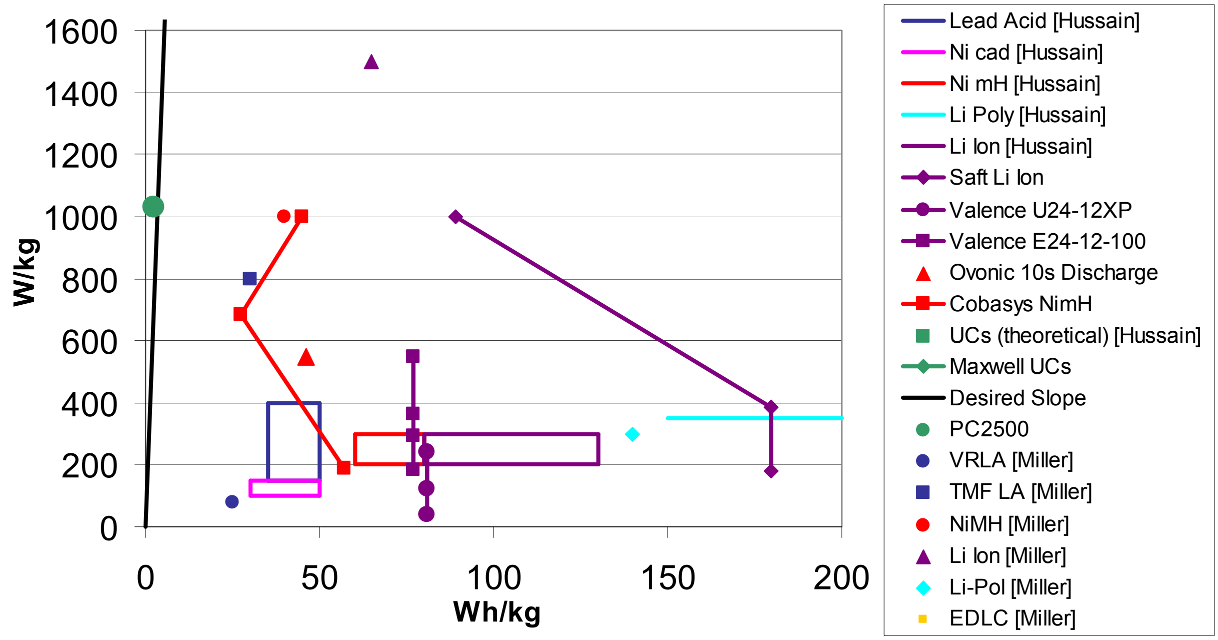


Figure 10: Detailed View of Electrochemical Storage and Maxwell PC2500 UCs [12-23]

	Specific Energy		Specifc Power		Effic	Cycle Life	Estimated Cost	
Storage Media	Wh/kg	Wh/kg	W/kg	W/kg	%		US$/kWh	
Lead Acid	35	50	150	400	80	500-1000	100	150
Nickel Cadmium	30	50	100	150	75	1000-2000	250	350
Nickel Metal Hydride	60	80	200	300	70	1000-2000	200	350
Aluminum air	200	300	100	100	<50	na	na	Na
zinc Air	100	220	30	80	60	500	90	120
Sodium sulfer	150	240	230	230	85	1000	200	350
sodium Nickel chloride	90	120	130	160	80	1000	250	350
Lithium Polymer	150	200	350	350	na	1000	150	150
Lithium Ion	80	130	200	300	>95	1000	200	200
UCs (theoretical)	na	15	na	4000	na	0.5M to 1M	9500	Na
PC2500	2.344	na	1030	na	na	na	na	42667

Table 3: Energy Storage Media Specifications [12, 22, 24]

Table 3 shows some of the data for the specific energy and power of various energy storage media shown in the above figures along with efficiency, cycle life and estimated cost. The estimated cost listed for theoretical ultracapacitors was a slightly more recent cost estimate because of the difference in publication dates of references and the cost for the PC2500 cells used in the WVU ESS, which were shown at actual retail cost per kilowatt hour. Since these technologies were all changing rapidly, the costs changed significantly over time. The remainder of the data was from Hussain's book. Note that ultracapacitors had cycle lives orders of magnitudes larger than other electro-chemical storage technologies [13]. “Unlike an electro-chemical cell that functions by virtue of the Faradic process of ionic transfer, an ultracapacitor is a non faradic process that is simply charge separation and no electronic transfer. In a conventional capacitor, the energy storage effect is purely a surface phenomenon, so most of the materials used are there for structure, not for energy storage. UCs, however, achieve phenomenal surface area for rather finite plate areas by having porous electrodes that are dense with crevices and pores. A battery makes the best use of available materials because the electrode mass contributes in a Faradic process to the energy storage task. However, the Faradic process involves ion transfer so there are transport delays and time dynamics to contend with. Capacitors, and UC’s, have very fast pulse response times because only stored charge is removed or restored at the interfaces rather than reactions occurring in the bulk electrode material. By extension, this means that UC’s have cycle life orders of magnitude greater than electro-chemical cells. It is not unreasonable to expect a UC to provide several million cycles in use.”[13]

“The energy density projections do indicate that there are good possibilities for achieving battery-like energy densities with continuing development of materials for ultracapacitors.” [6]

Energy Storage Media Efficiency

The internal resistance of the energy storage components is responsible for the bulk of the efficiency losses associated with them. The power loss associated with the internal resistance, R, is calculated as:

$$\text{Power Loss} = I^2R$$

Equation (1)

where I is the current flowing through the cell. This loss is significant particularly for hybrid vehicles because these systems tend to operate at peak power levels. Figure 11 shows these losses in the three most relevant technologies for hybrid vehicles: Ultracapacitors, Lithium Ion and Nickel Metal Hydride. The ultracapacitor efficiency does not include a dc to dc converter. The lithium based technology appears to be as efficient as Ultracapacitors in this respect.

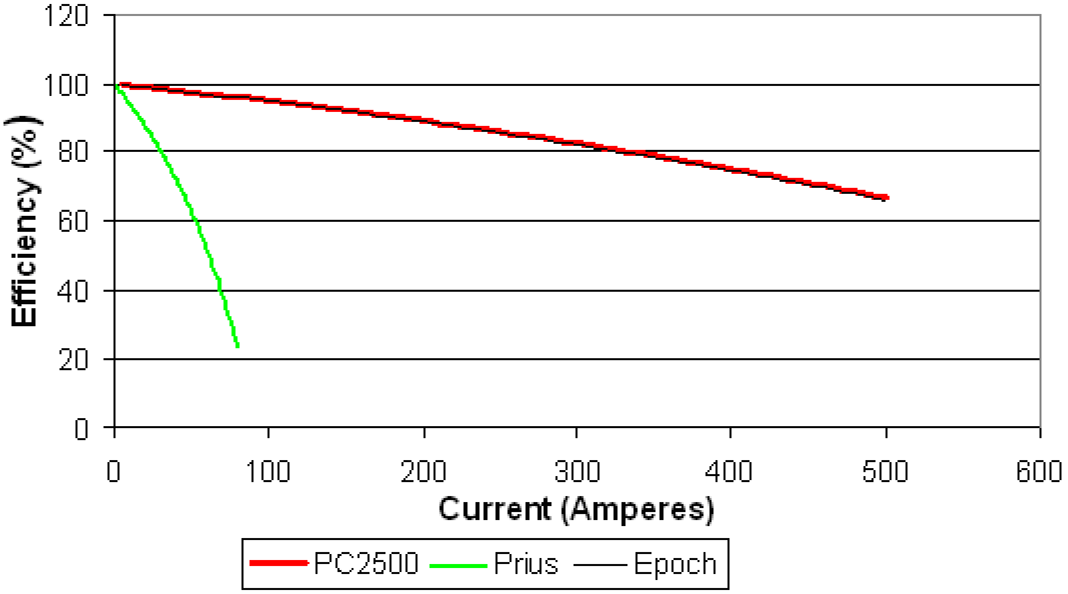


Figure 11: Effect of Internal Resistance Losses for UC, Li-Ion (Epoch) and NimH (Prius) Technologies [17,22,23,26]

$$E_{stored} = \frac{1}{2} CV_{Max}^{2} - \frac{1}{2} CV_{Min}^{2}$$

Equation (2)

Where C was the capacitance of the entire ESS, which was 585 Farads. V_{Max} was the upper voltage limit of either the capacitors pack as a whole or the motor controllers and V_{Min} was the minimum useful voltage of the electric motor controllers.

The maximum safe pack voltage recommended by the manufacturer was 57.5 volts. The motors selected could not be expected to use the entire voltage range, so some of the energy storage was not used. Note that the energy per volt at the lower end of the spectrum was much less than that at the upper range. The motor controllers limited the pack voltage to 20 volts initially, but in the end needed 22 volts to start functioning. This reduced the pack capacity by 142 kJ. After the motors were delivered, the maximum voltage was recommended to be limited to 50 volts, reducing the capacity further by 253 kJ. The remainder, 590 kJ or 0.17 kWh, was 60% of the total capacity of the ESS itself. Note that the energy lost in 7.5 volts at the high end of the voltage range was almost twice that lost in the 22 volts at the low end. If the storage capability at voltages in excess of 50 volts were to be used, 85.5% or 0.23 kWh of the capacity would have been useable.

The 0.17 kWh capacity allowed the vehicle to store most braking events and assist the vehicle in acceleration at full power for the time period of the acceleration in most cases. In John Conley's thesis [32], real driving data were analyzed for both highway and city driving and based on event energy, the majority of events could have been captured by the 590 kJ useful capacity of the WVU ESS. The data were analyzed based on both level and actual terrain. No city events and only one highway event exceeded the pack size on level terrain while two events for each exceeded the pack size with terrain taken into account [32].

The composite acceleration profile, compiled from the 2007 competition cycle described in Figure 12 was used to calculate the ESS voltage based on maximum motor usage over the speed profile starting from a full pack. The original motor specification and the de-rated curve are shown. With the original specification, the pack reached approximately 38 volts or 49.7% SOC. With the motors de-rated, the pack reached only 45 volts, which correlated to an SOC of 77.4%.

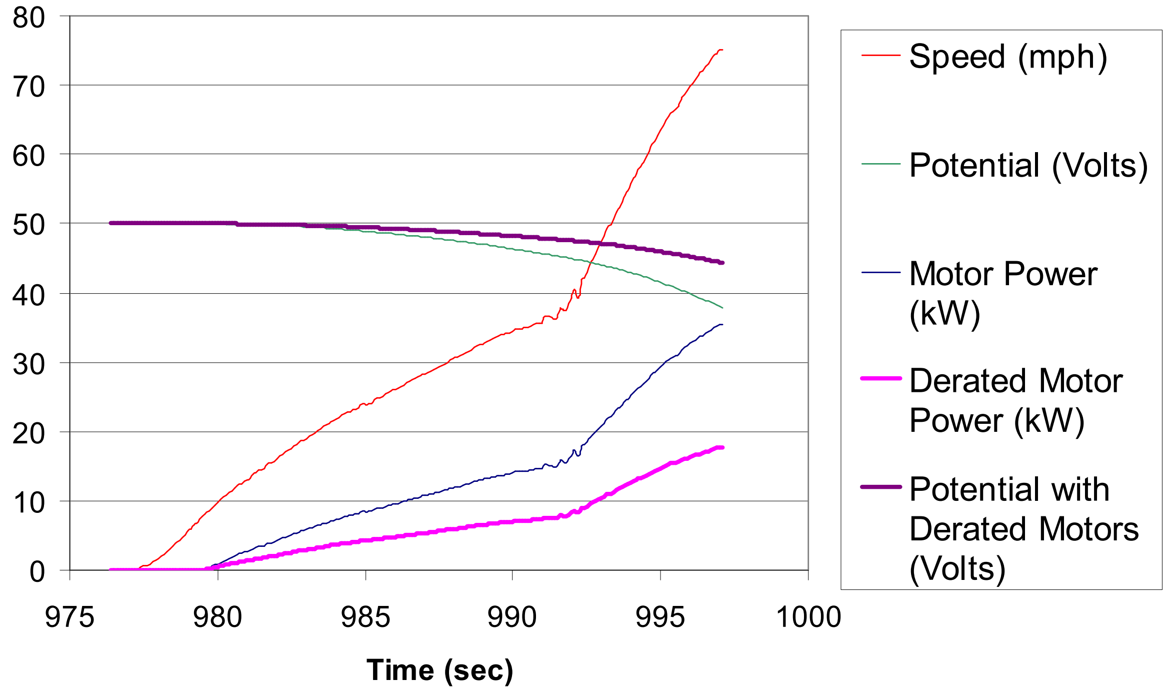


Figure 12: ESS Voltage and Motor Power During Acceleration

A combination of batteries and ultracapacitors was also considered. However, the primary goal of the team's hybrid strategy was to recapture energy and reuse it quickly, so there was little advantage to this storage system, since it meant a decrease in overall efficiency. Several tests have shown that ultracapacitors in parallel with batteries acted as a buffer for the high power events associated with hybrid drive systems. Tests with direct connection and with a converter separating the ultracapacitors from the batteries have improved the efficiency of batteries as storage media and has reduced the package size and has increased the life cycle of the batteries by reducing peak currents [31]. Miller calculated that the total system mass could be reduced by 43% using a voltage converter to connect an ultracapacitor pack to a battery pack, allowing the use of more of the capacitor's voltage range and therefore more of its energy storage capability [13]. Regardless of any positive effect the ultracapacitors had on battery efficiency, the transfer subsequent to capture would not have been as efficient. The idea of a dual storage system was to gain the energy and power density of the two storage systems by charging or discharging the power dense system quickly and transferring energy to or from the energy dense system. This latter transfer of energy was a key deficiency in this concept.

The second transfer of the energy had an efficiency cost. So, regardless of the efficiency of the storage systems or the transfer from one to another, some energy would have been lost. The additional loss of energy could have been countered by the reduction in vehicle weight. The energy storage components of the WVU ESS system weighed 216 pounds. With the 43% reduction in weight from a combined system according to Miller, the system would have weighed 93 pounds less.

With the original weight of the WVU Equinox at 2008 kg, 12.01 kWh of energy was required for the competition cycle. With the 43% reduction in ESS component weight, the vehicle would have weighed 1966 kg and it would have required 11.93 kWh of energy for the cycle. This reduction in vehicle weight would have reduced vehicle energy use over competition cycle by 0.08 kWh. Since this reduction in weight would have reduced the energy required at the wheels of the vehicle, a conservative net energy recovered at the wheels was used. The projected reduction was 5.4% of the 1.47 kWh of energy capable of being recycled in the ESS over the competition cycle. Note that the capability of the pack was used here rather than the energy actually stored because the pack was unintentionally oversized for the capability of the rest of the hybrid drive. A reduction in energy of 5.4% would not have been insignificant; however, it would not have been likely to off set the energy loss from the converter.

Engine and Transmission Selection

The stock vehicle had a gasoline engine producing 183 hp mated to a five speed automatic transmission. With the motors providing peak power, less power was required from the primary energy converter and therefore the team chose to use the 150 hp GM Diesel engine for primary propulsion packaged with a six speed automatic transmission.

In Figure 13 and Figure 14, the torque at the wheel hub is shown for the Stock Equinox powertrain and the GM Diesel powertrain in each of these transmission’s respective gears as if the torque converter were locked up. Figure 13 shows the hub torque for the GM Diesel powertrain with the electric motors at maximum capability while Figure 14 shows the two powertrains without the electric motors. To clarify, the maximum capability here of the electric motors was based on the product as received, not as advertised, nor as ordered.

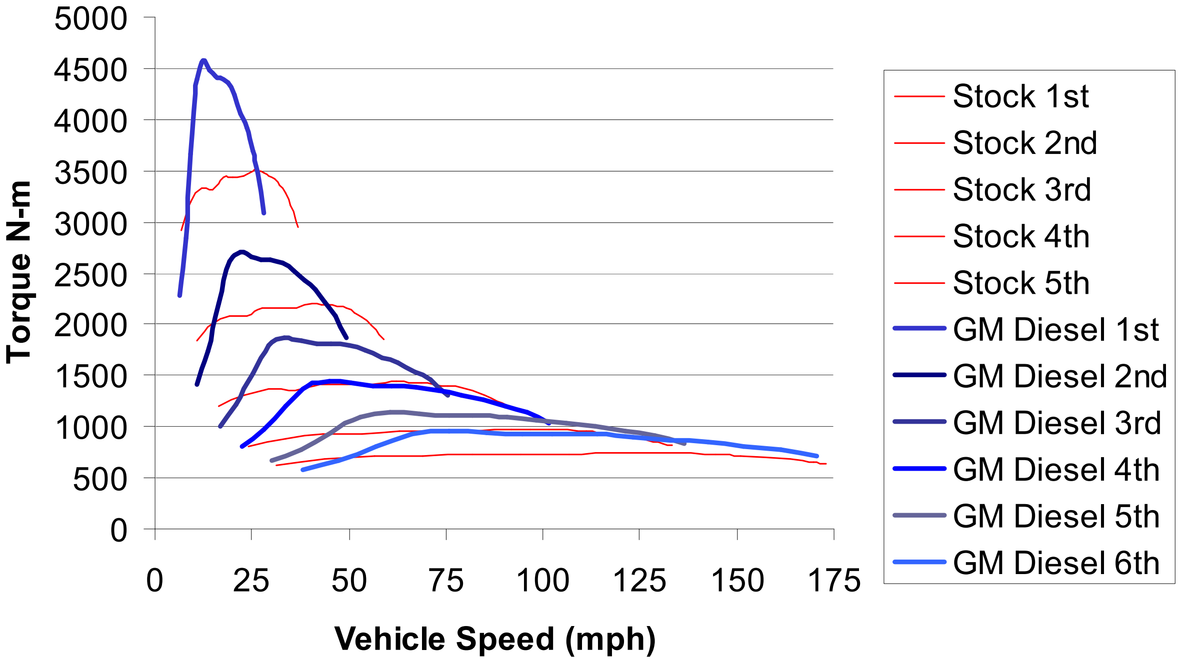


Figure 13: Road Torque for Stock Equinox and GM Diesel Powertrains with PML Motors (derated)

The author has inspected the 1.9 liter GM Diesel and noticed several advanced emissions control devices such as liquid cooled exhaust gas recirculation, intake swirl actuators, common rail injection, variable geometry turbocharger, and a diesel particulate filter (DPF) managed by the engine ECU. The selection of a diesel engine also allowed the team to use a more emissions friendly fuel-B20 Biodiesel.

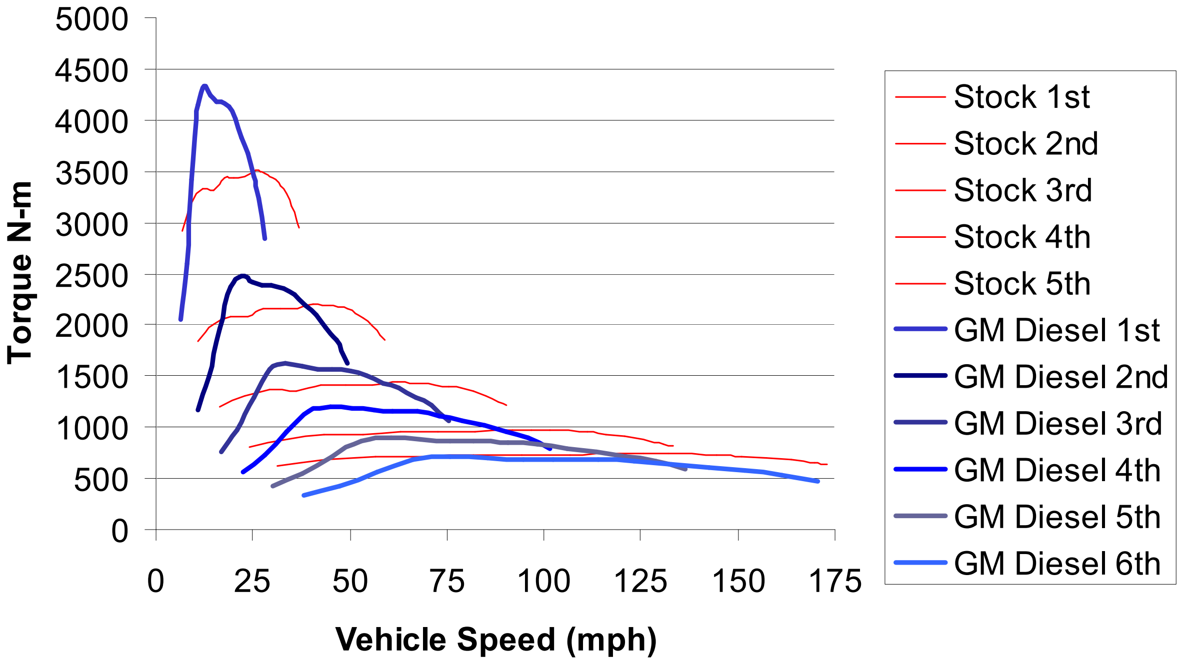


Figure 14: Road Torque for Stock Equinox and GM Diesel Powertrains without PML Motors

Argonne National Laboratory's GREET 1.8b showed some of the reasons the team chose B20 biodiesel to fuel the vehicle. This program estimated energy use and emissions from the source of the fuel to the pump and as the fuel was used in the vehicle. The program accounts for the different ways the fuels were produced and how it was used in the vehicle.

Table 4: ANL GREET 1.8b Petroleum Use, Greenhouse Gas and Regulated Emissions

	RFG	E85	B20	H2
Total Energy Btu/mi	6681.03	12026.98	12362.58	9286.94
Fossil Fuels Btu/mi	6297.93	4660.65	5109.91	9121.49
Petroleum Btu/mi	5628.21	1902.66	4547.99	88.81
CO2 g/mi	484.39	357.99	361.22	587.67
CH4 g/mi	0.60	0.61	0.47	1.92
GHGs g/mi	505.82	429.12	377.46	636.52
CO: Total g/mi	5.28	5.43	0.87	0.16
NOx: Total g/mi	0.51	0.93	0.48	0.39

The values shown in Table 4 were calculated for the four fuels used in the competition. These were well-to-wheel estimates for hybrid vehicles. The reformulated gasoline (RFG) and E85 ethanol values were calculated for a spark ignited engine while the B20 numbers were calculated for use in a compression ignition engine and hydrogen numbers were calculated for use in a fuel cell. The program showed that B20 produced fewer greenhouse gases and NO_x than the other fuels.

Control Strategy

Since the hybrid system was designed primarily to scavenge energy that would otherwise be lost, the team's goal was also to capture that energy efficiently so as to maximize the benefit from the hardware. Foremost was the efficient storage of energy, hence the ultracapacitors with roughly twice the efficiency of any suitable media. This led to the requirement that there would always be room to store any energy available for capture. This was less important with conventional energy storage media since the limiting design factor was usually power density, which left the vehicle with an abundance of long term energy storage. With ultracapacitors, energy density was a limiting factor. Since the capacitors were only capable of holding a few smaller events or even a single twenty second event at peak regeneration from the electric motors, there was a possibility that the pack could be full when the next event was available for capture. This lead to the conclusion that it was better to use the stored energy relatively quickly even under less efficient conditions than to have a full ESS when the next potential event was reached.

The essence of a hybrid control strategy was in preparing the vehicle to meet driver demand and cope with future events. The unknowns of future events included driver demand, vehicle state and grade. Driving style could have been predicted via artificial intelligence methods to an extent and GPS information could have been used to improve the control strategy's knowledge of the future, but none of this information guarantees future vehicle operation. The current states of the vehicle and driver request were the best information available to prepare the vehicle for the future. The strategy could have either prepared for the worst future case or it could have accepted losses if that case were to become reality.

With a relatively small storage capacity, the most important information needed by the control strategy was when the next regenerative event would occur and its size. The closest information to that was the current state of the vehicle. This information was used to identify the next possible actions of the vehicle and allowed the control strategy to plan for those actions. If it was traveling at highway speed, it was likely that the next event was going to be a relatively large braking event. If the vehicle was stopped, the next event was likely to be an acceleration. If the vehicle was traveling at an intermediate speed and the driver was depressing the accelerator significantly, it was likely that for some portion of the immediate future, the vehicle was going to increase its speed, rather than slow down and reduce its kinetic energy. In fact, there was a definable amount of energy stored in the vehicle as kinetic energy, so at any given moment, the amount of energy that could have been recaptured was known. Of course, depending on the rate of deceleration, only a portion of that energy could have been captured because of the limitations of the hybrid motors.

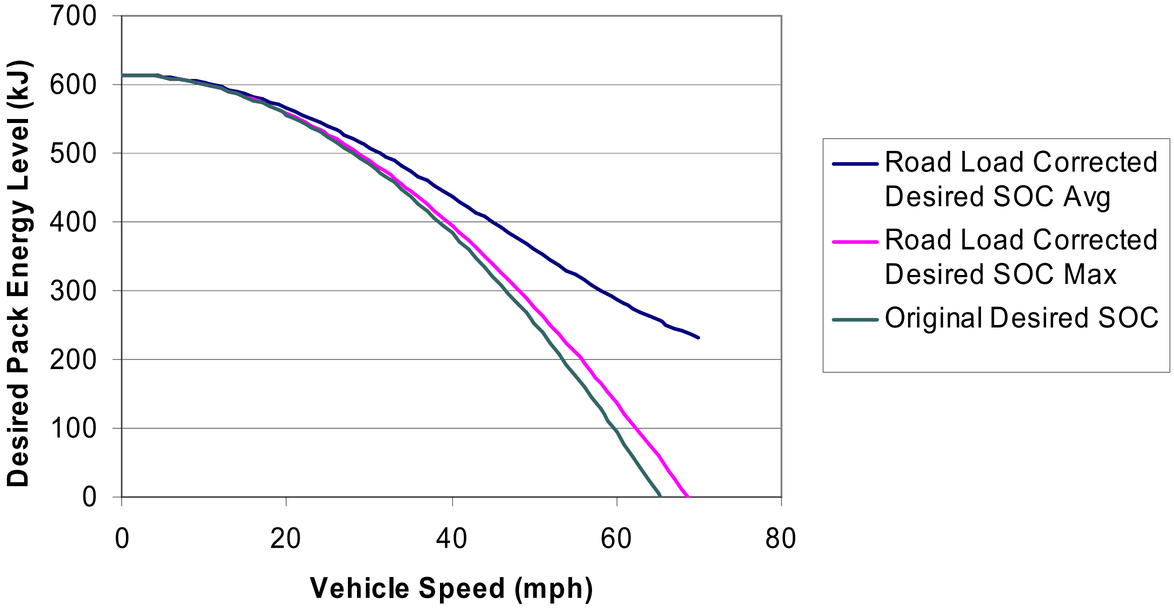


Figure 15: Desired SOC Relative to Vehicle Speed

The original desired SOC shown in Figure 15, and described in Equation (4), was simply the energy capacity of the ESS, as in Equation (2), less the kinetic energy of the vehicle based on its speed as in Equation (3).

$$E_{mass} = \frac{1}{2} MV_{vehicle}^{2}$$

Equation (3)

$$SOC_{desired} = E_{stored} - E_{mass}$$

Equation (4)

In reality, the parasitic road load losses affected the energy that could be captured. These numbers varied widely depending on how fast the vehicle decelerated. From the year three fuel economy drive cycle, an average and maximum deceleration were determined. These numbers were used to determine the difference in the energy that was available for capture.

For a given speed x, the parasitic losses, $E_{Parasitic}$, given the average or maximum deceleration, a, was:

$$E_{parasitic} = \frac{C_d A \rho}{2a} \int_0^x V^3 dV + \mu Mg \int_0^x V dV$$

Equation (5)

Where V was the vehicle speed, C_d was the vehicle's coefficient of drag, A was the vehicle frontal area, ρ was air density, μ was the rolling resistance coefficient for the vehicle, M was the mass of the vehicle, and g was the acceleration due to gravity.

Figure 15 shows the difference between the max and average deceleration curves. Significantly higher headroom is shown with the average deceleration at higher speeds. This could be interpreted as extra storage space that was not really needed for this strategy, or as space that could be used to store energy for longer periods of time to be used at the most strategic time while driving.

It should be noted that this approach did not account for changing elevation, which affected this strategy substantially. A regenerative event was much smaller or much larger when an uphill or downhill grade was encountered, so additional energy available for recapture was lost in the downhill cases.

Inputs

Brake Pedal Position provided the input data for the regenerative braking strategy. The command to the motors for regeneration ramped up steeply as the pedal was depressed in order to recapture maximum braking energy. The total braking capacity of the motors was relatively low, so the driver hardly noticed their impact on slowing the vehicle.

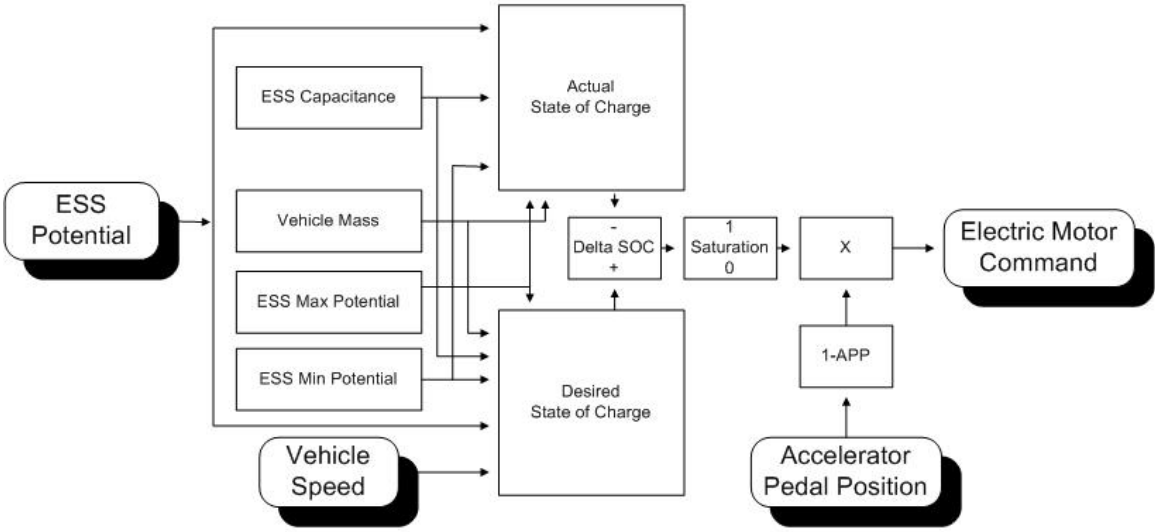


Figure 16: Flow Chart of Conceptual Control Strategy

The accelerator pedal position (APP), actual state of charge, vehicle speed, and vehicle weight (for calculation of potential energy) were the input variables used to determine how best to use the stored braking energy to reduce the fuel consumption and emissions of the vehicle.

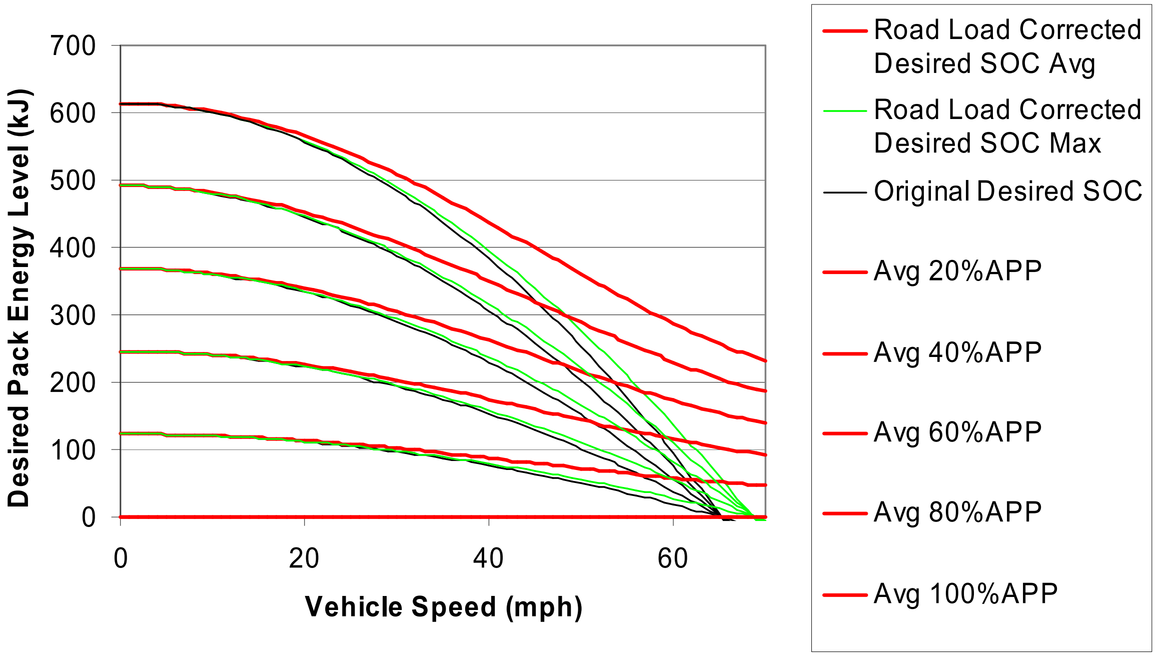


Figure 17: Desired State of Charge with Accelerator Pedal Position (APP)

The strategy used these variables to determine a desired state of charge, which compared with the actual state of charge determined the available useable energy. It was difficult to determine the future state of the vehicle. However, the speed range of the vehicle was finite and there was a specific amount of energy that was available for regenerative braking at a given speed, so the primary goal of the desired state of charge was to allow the UC pack to be able to capture as much of that energy as possible. Figure 16 shows a flow chart of the strategy described above. The figure shows which function each variable effects. As the APP increased the desired state of charge decreased, but was still based on the vehicle's speed.

Outputs

The primary goal of the control strategy was to determine based on the above inputs what torque request to send to the engine and electric motor controllers to maximize fuel economy and minimize emissions from the engine. The strategy resulted in a torque request to the diesel engine and wheel motors.

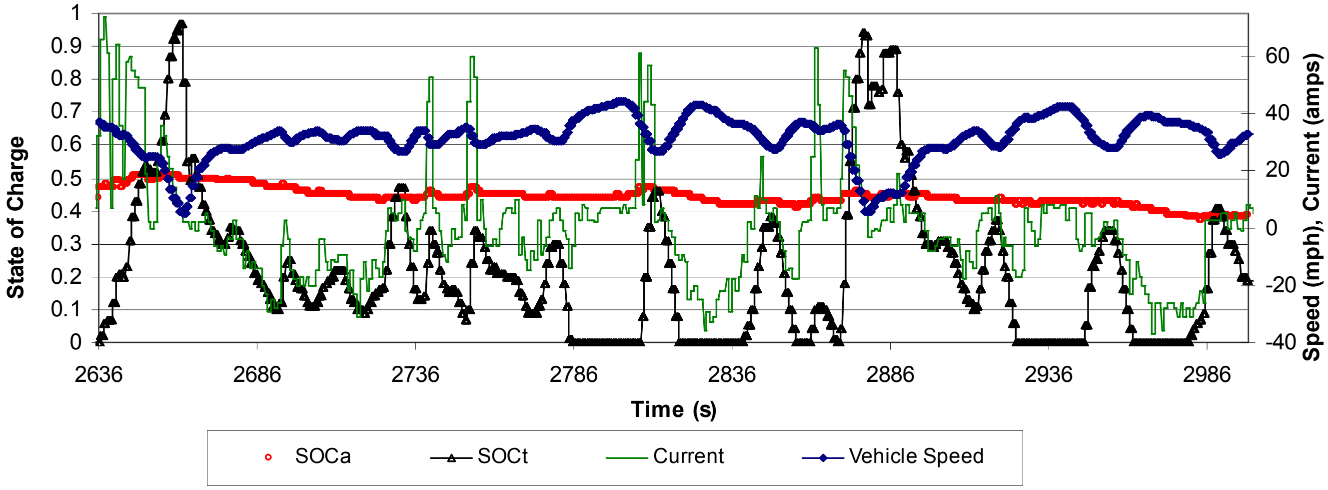


Figure 18: Desired State of Charge during Normal Operation

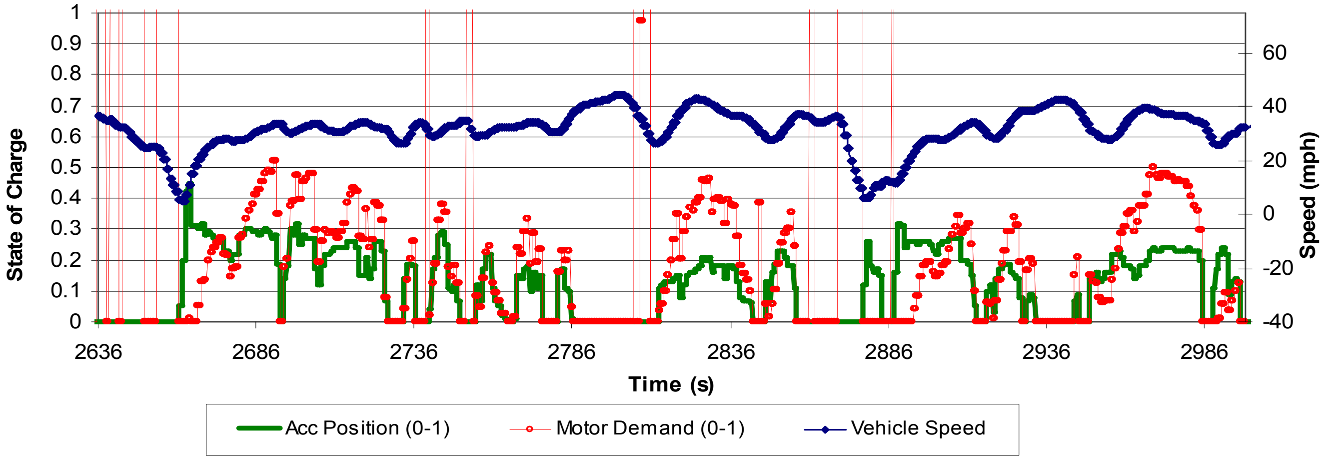


Figure 19: Driver Demand and Motor Demand Corresponding to Normal Operation Above

Figure 18 shows data logged on no particular route around Morgantown, WV in medium to low speed stop and go traffic over significant variable terrain. The data logged showed how the inputs described effect the outputs of the control strategy. The SOC_a and SOC_t are shown on the left scale while the current and vehicle speed are shown on the right hand scale. Positive current denoted regeneration. Notice that when SOC_t was below the SOC_a value, current flowed from the ESS to the motors when required. Also notice the relationship of speed to SOC_t. From the change in speed, one can determine when the vehicle was accelerating and along with the SOC_t, when the accelerator was substantially depressed. Figure 19 shows the corresponding driver input and motor request as a non-dimensional proportion.

Design Decisions

Inboard vs outboard hybrid motor placement

In year one, the vehicle was designed with direct drive motors and it was decided that those motors should be mounted outboard of the suspension and that the wheels should be mounted directly to them. This decision was made with a reduction in parts and energy losses as well as packaging in mind. In year two the motor placement was moved inboard of the suspension due to concerns over the unsprung weight of the motor, especially since the required tire package already increased the unsprung weight substantially over the original package. Heat from service brakes would have also increased cooling load for the motors.

Ultracapacitor Energy Storage Sizing

The braking horsepower for the competition cycle was in excess of 300 hp and certainly did not reach the capacity of the service brakes. It was neither practical nor cost effective to place a 300 hp motor in a 4000 lb. SUV. At some point, as the size of the motor increased, the value of that additional capacity diminished. The thesis of John Conley [32] provided a suggestion as to an initial motor size of approximately 50 hp, which provided a power level the ESS would be required to supply and absorb. This gave a rate of energy transfer, which indirectly affected the sizing. The basic premise for the ESS was that it should capture one energy event and then use it. The maximum event size was a 70mph to zero deceleration or an acceleration from zero to seventy. The final size of the to ESS, 0.17 kWh of useful energy, resulted in an ability for it to power the originally specified motors, 800 amp peak, for 15.3 seconds.

Communications Bus and Sensor Information Collection Design

In order to integrate the communications buses from the stock vehicle successfully, the new powertrain, and the electric motor controllers had to be properly managed. In addition to stock and powertrain message conflicts, the separation of the two busses allowed messages to be manipulated or converted. A third bus was required to integrate the electric motor controllers. The motor controllers' CAN bus operated at a completely different speed than the GM products, so it was not compatible with the two busses required for their integration. With a requirement for three separate busses, two controllers were required. This requirement was used to reduce the amount of wiring and to distribute data collection within the vehicle. In year two, the controllers were positioned relatively far apart, with one located in the front right quadrant of the engine bay and one in the left rear cargo area of the vehicle. The front controller was tasked with the integration and data collection requirements for the diesel powertrain and the stock vehicle. It also housed the actual control strategy for the hybrid powertrain. The rear controller was used to communicate with the electric motor controllers and controlling and monitoring the ESS. In year three, the front controller was moved to the area under the front passenger seat. This location was not closer to the items that needed to be controlled, but it allowed better use of engine bay space.

Electronic Accelerator pedal position sensor

In order to implement the strategy originally designed by the team, the vehicle needed to receive the input from the APP, decide in what proportion the two power sources would provide the desired torque request, and command those two sources. The controller chosen allowed the team to read the APP and make that decision as well as command the electric motors via the communication bus to provide the necessary torque, however, the controller could not directly provide the request to the diesel engine. It required two proportional analog signals while the controller could only provide a digital signal. A device was needed to convert the controller's digital signal to the conventional analog throttle signals. A National Semiconductor LM 331AN chip was used to convert a variable frequency to a variable voltage in conjunction with a relatively simple circuit. The board, shown in Figure 20, used two of these chips to emulate the original APP signal according to the vehicle controller's commands.

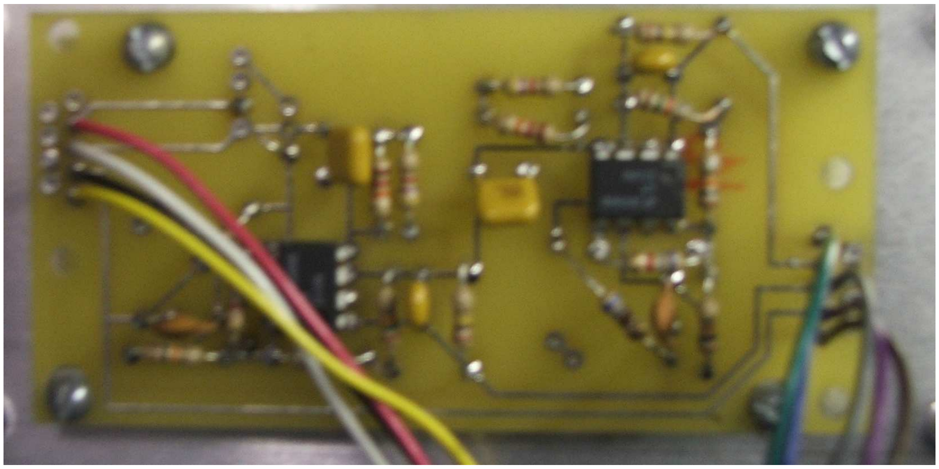


Figure 20: Frequency to Voltage Converters for APP Signal

Initially, the emulator met the requirements and the signals were of sufficient accuracy for driving and the engine found the signals to be sufficiently proportional to be considered valid and limp home mode was not entered. It was noticed that a minute change in commanded frequency would cause a completely new result that could be 5 to 10% different from the previous result. A feedback loop was added to the controller using the desired torque, as determined from the APP input, broadcasted by the engine. The controller used this signal to adjust the frequency output to the converter board to properly meet the demand from the control strategy.

Fuel Economy Testing

A hybrid vehicle has an energy storage device on board, which could contribute to the energy the vehicle requires for propulsion. If the ESS were to start a fuel economy test with a high SOC and ends with a low SOC, an energy source was used to propel the vehicle during the test that was not included in the fuel economy measurements. If the change in energy were significant, the fuel used during the test would not accurately reflect the fuel economy of the vehicle over the test cycle.

To analyze the WVU vehicle's energy potential for this problem, the total useful energy storage capability of the ESS was compared with energy of the 2007 competition cycle energy. The useful energy stored in the ESS, 0.17 kWh, was only 1.39% of the energy, 12.19 kWh, used to propel the vehicle over the competition cycle. It should also be noted that the cycle itself was a variable in this problem. If a longer cycle were to be used, this problem would be less significant. However, a large ESS could make avoiding SOC correction in this way impractical.

The SAE Recommended Practices J1711 contained specific methods for correction and for determining when correction was necessary. With the goal of measuring fuel economy within +/-3% of the vehicle's true fuel consumption, a limit of +/-1% change in state of charge with respect to the total fuel energy used over the cycle is allowed without state of charge correction. [7] By using the energy expended rather than the energy required, the possible error of the fuel economy was more accurately analyzed.

Using the fuel energy published in the competition rules of 17,923 btu/lb of fuel for B20 biodiesel and 21.63 lbs of fuel for the total route resulted in 113.5 kWh for the route-based energy used. The capacity of the ESS, 0.17 kWh, translated to a maximum change in stored energy of 0.15% per SAE J2711 described above. The WVU ESS was substantially smaller than a system that would require correction. The route could be shortened or the fuel economy could increase tenfold without requiring SOC correction.

Competition Test Route

Testing for the 2007 Challenge X Competition took place at General Motors' Michigan Proving Grounds (MPG) in Milford, Michigan. The data shown throughout unless otherwise stated was taken there on the circle track. The general terrain of MPG varies; however, this track did not have changes in elevation around its circumference.

The fuel economy portion of the competition followed a prescribed speed profile on the circle track. The profile was representative of a combined city and highway driving situation. There were multiple stop and go maneuvers as well as a three steady state segments at 35, 55, and 75 mph.

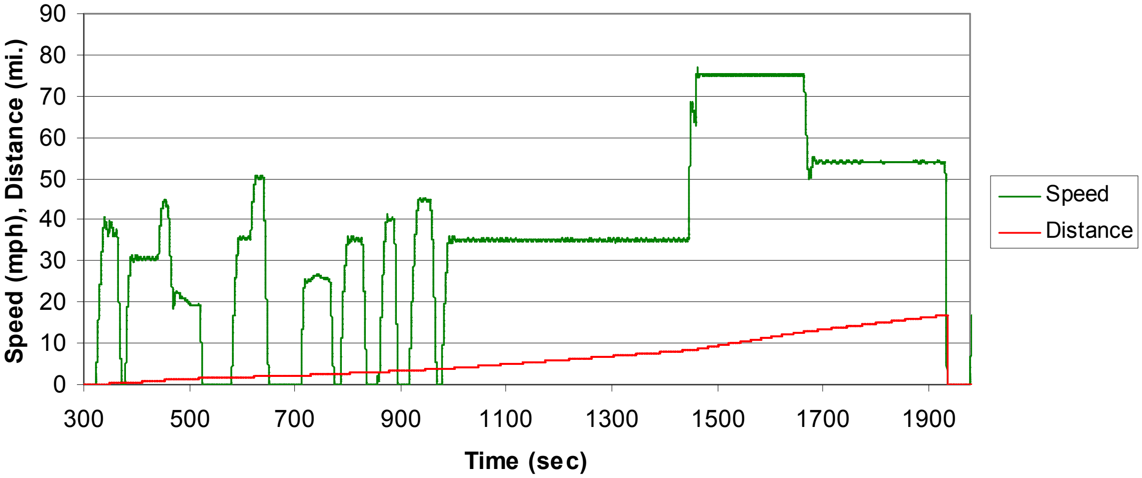


Figure 21: Speed Profile followed during 2007 Competition.

The data taken for the fuel economy route with this profile was comprised of three of these profiles in succession as shown in Figure 22.

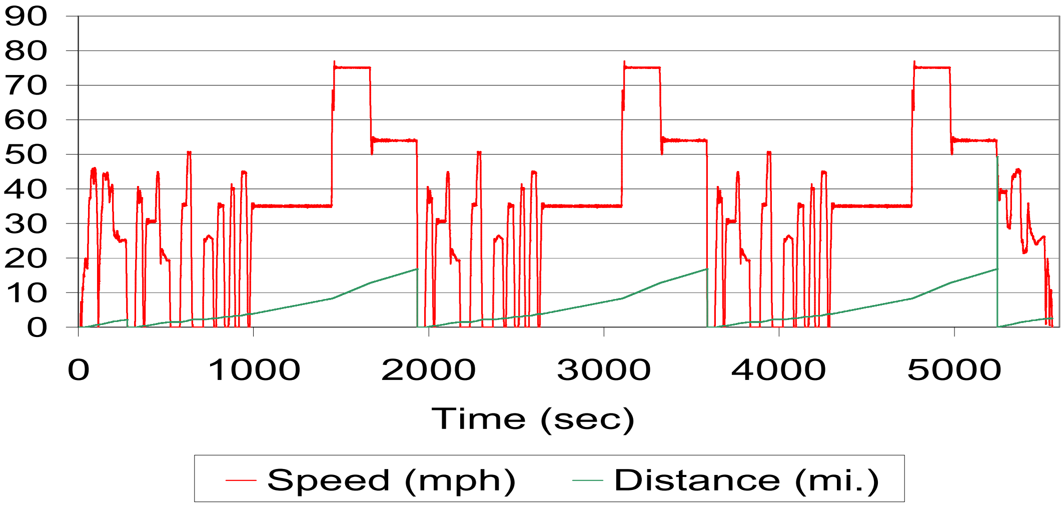


Figure 22: Complete Cycle followed during 2007 Competition

For a conventional vehicle of the same weight, 12.19 kWh of energy was required to drive the full cycle. For an infinite hybrid, one that was capable of capturing all of the braking energy required for the cycle, the energy captured would have been 2.83 kWh. If that energy were reused with no losses, the energy required for the cycle would have been 9.36 kWh. This assumed infinite storage and hybrid propulsion system, an optimistic usage of energy and a light-as-air hybrid system. This would have been a 23% improvement in energy usage over the conventional vehicle of the same weight.

To account for the efficiency losses as the energy passes from the road through the electromechanical devices to the storage media and back again, a storage efficiency of 80% and a motor and drive efficiency of 90% were assumed for each transfer. These reduced the usefulness of the required braking energy to 1.47 kWh. The energy required to drive the cycle was 10.72 kWh, which was a 12.03% improvement in energy efficiency.

In Figure 23, the instantaneous road load power was sorted for the entire cycle to illustrate the amount of time that each power level was required. The peak power and braking requirements for the competition cycle were 208 kW and 344 kW respectively. The calculated propulsion power was greater than 136 kW (183 hp), the stock performance level, for 15.2 seconds and greater than 107kW, the total combined power for the WVU vehicle, for 17.6 seconds. Braking power was greater than 300 kW for 0.6 seconds and greater than 50 kW, maximum power for WVU ESS, for 49 seconds of the total 553 seconds of the cycle requiring braking effort. The power required over the cycle was sorted and shown in Figure 23.

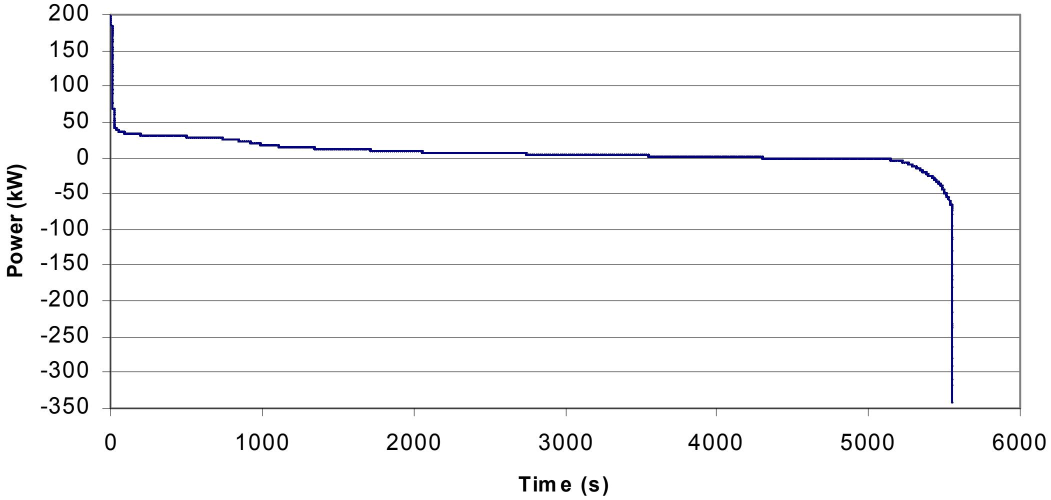


Figure 23: Road Load Power for Competition Cycle Sorted by Power Level

Notice over the entire time period of the cycle, the small amount of time that required peak propulsion power. The braking power was expended over a shorter time period than the propulsion power. However, the power required was still much less than the peak propulsion power requirements for the majority of the cycle time that required propulsion power.

Figure 24 shows the braking power over time that was less than 50 kW. This figure represented 93.8% of the cycle time requiring braking power. The braking power in excess of 40kW required the dissipation of 17% of the braking energy for the cycle. In turn, the power in excess of 50 kW dissipated 10% of the braking energy.

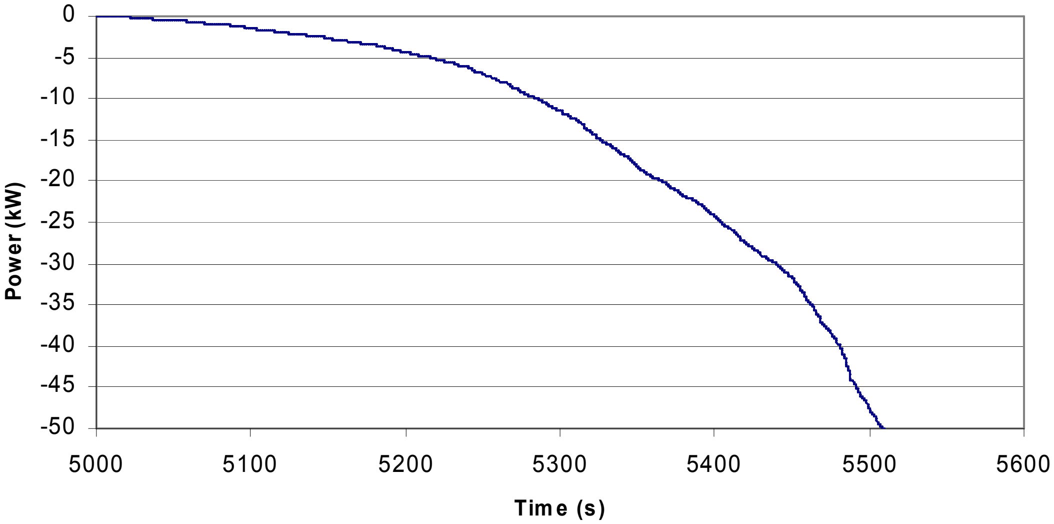


Figure 24: Sorted Braking Power less than 50 kW

Results

Table 5 shows the results of the on-road fuel economy event and the 20% improvement demonstrated by the WVU Equinox over the stock vehicle in year two.

Team	Primary	Fuel Density	Start weight	Final Weight	lbs fuel	vol fuel	distance	Mileage
	Fuel	Lbs/gal	lbs	lbs	lbs	gal	Miles	MPG
WVU	B20	6.9935	61.14	34.34	26.8	3.83213	88.14	23.00
Control	RFG					4.59997	88.14	19.16

Table 5: Year Two Competition Fuel Economy Results

At competition in year two, the vehicle had excessively high CO emissions (3.22 g/mi. in year two versus 0.31 g/mi. in year three) because the engine lacked an ambient temperature signal. This caused the engine to default to a very low ambient temperature and inject excess fuel, which obviously hurt the fuel economy to some degree in the year two competition.

Team	Primary	Fuel Density	Start weight	Final Weight	lbs fuel	vol fuel	distance	Mileage
	Fuel	Lbs/gal	lbs	lbs	lbs	gal	Miles	MPG
WVU	B20	7.09	63.09	41.46	21.63	3.05	71.05	23.30
Control	RFG	6.12	22	0	22	3.6	71.05	19.74

Table 6: Year Three Competition Fuel Economy Results

Table 6 shows the fuel economy event results for the 2007 Challenge X competition. The vehicle showed an 18.03% improvement in fuel economy over the stock vehicle.
During the fuel economy testing, the electric motors malfunctioned. At approximately 70 mph the motor controllers would cease to control the motors, causing uncontrolled power generation from the permanent magnet motors. The motors would continue to regenerate until the vehicle was slowed to approximately 20 mph. This occurred at the same point in the speed profile of the fuel economy route each time it was repeated. The hybrid system functioned as intended throughout the other portions of the testing.

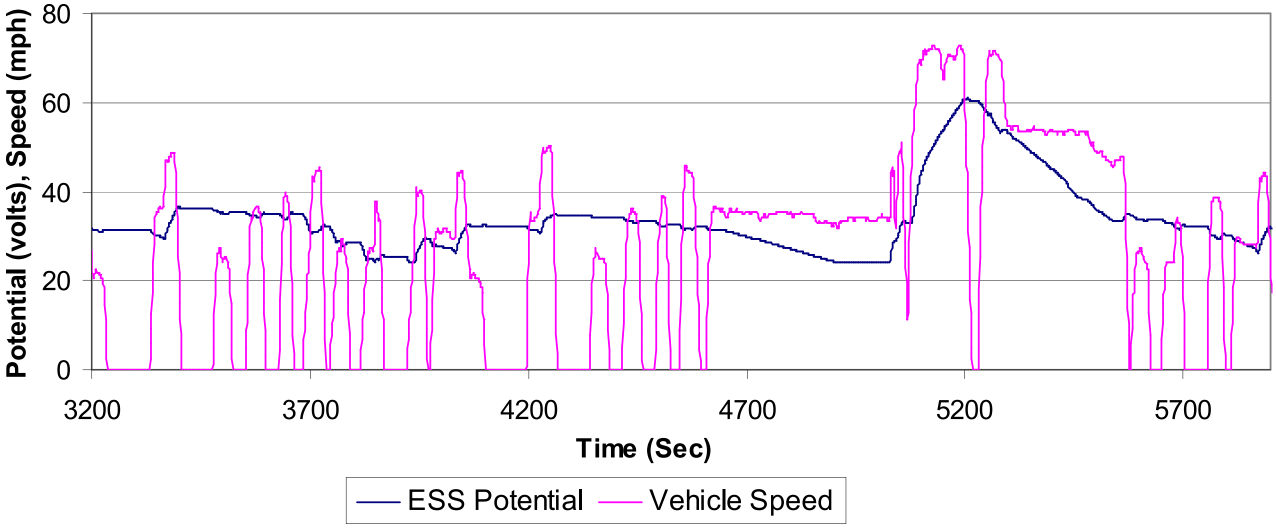


Figure 25: Large unintended Regeneration Event with associated increase in Voltage

Figure 25 shows one portion of the data taken during the fuel economy test where the ESS was charged above its desired capacity and the vehicle was forced to stop to allow the controllers to regain control of the motors and then continue on the course. The stop of the vehicle and the end of the large voltage rise resulting from the uncontrolled regeneration are shown shortly after 5200 seconds in the figure. The same profile was followed two other times and at the same point in the profile the same error occurred. These unintended regeneration events had a significant effect on the fuel economy of the vehicle.

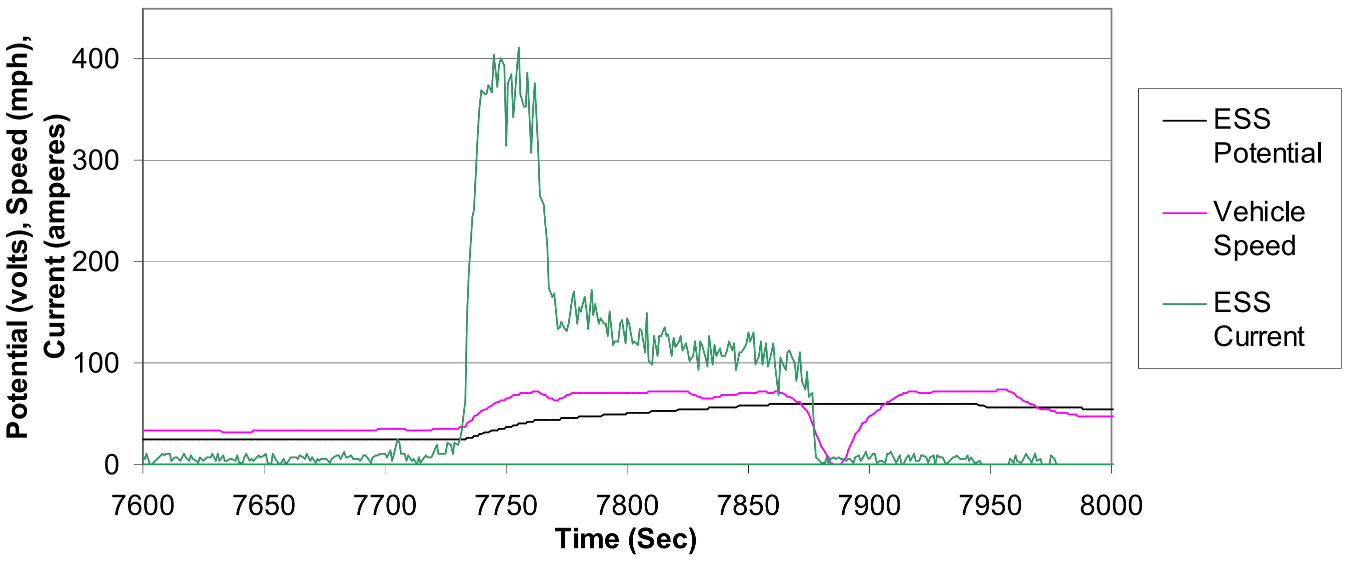


Figure 26: Large positive Current here indicates Regeneration

The road load energy from the stop at approximately 7885 seconds in Figure 26 to the point where highway speed was again reached was 1.24 kWh, cumulative. The regeneration from the point where the vehicle started accelerating to 70 mph from 50 mph caused the storage of an extra 0.91 kWh of energy. This energy was, of course, used again to propel the vehicle, but at a significant loss in efficiency through the hybrid drive train. As this energy was being stored, the energy integrated from the current measured from the motor drives versus the energy integrated from the change in ESS voltage showed an efficiency in the ESS of 82%. If 90% efficiency was assumed for the motor and drive electronics, the energy lost at the road and which consequently caused an increase in fuel consumption was 1.01 kWh. If the same ESS and motor efficiency were assumed for the use of the unnecessarily stored energy, a gain of 0.55 kWh was used to propel the vehicle. The resulting net loss of energy was 0.46 kWh.

Event Data					Captured Energy (kW-hrs)					
	Time (sec)		Voltage		Based on ESS Voltage			Based on Measured Current		
Event	Start	End	Start	End	Start	End	Event Energy	Start	End	Event Energy
1	2319.135	2444.315	24.02	59.08	0.2583	0.4957	0.2374	0.2555	0.5433	0.2878
2	5027.159	5206.286	24.21	60.97	0.7485	1.0036	0.2552	0.7778	1.088	0.3101
3	7716.896	7874.123	24.09	60.59	1.288	1.5368	0.2488	1.3527	1.662	0.3093
						Total	0.7414		Total	0.9073

Table 7: Energy Loss from Undesired Operation

To this point in calculating the fuel economy of the vehicle without the unintended events, the calculations involved fairly obvious efficiencies and the data allowed the events to be broken down into specific losses and gains. However, the engine and powertrain efficiency during these events was not easily estimated. The range of efficiency of the drive train was somewhere between 15% and that of the engine itself. Figure 4 showed average drivetrain losses for a conventional vehicle over some cycle. These values included idling and low power operation and the efficiency of the engine and powertrain at high power for these events was likely to be closer to the peak efficiency of the engine itself. If an engine efficiency of 35%, a reasonable assumption for a diesel engine without accessories or drivetrain losses, was assumed for the unwanted acceleration event and the undesired charge event, fuel energy was estimated at 4.87 kWh. The competition fuel was a 20% blend of biodiesel and conventional petroleum based fuel with a lower heating value of 17,923 btu/lb. The fuel wasted during the three undesired events using this conservative estimation was 0.926 lbs. This translated into a new fuel economy for the 2007 competition of 24.33 mpg or a 23.26% improvement over the stock vehicle.

	Time (sec)		Acceleration Energy (kW-hr)		
Event	Start	End	Start	End	Event Energy
1	2495.388	2524.43	4.4746	4.9064	0.4318
2	5228.378	5254.356	10.5596	10.9624	0.4028
3	7887.221	7915.192	16.1088	16.5146	0.4058
				Total	1.2404

Table 8: Energy Loss during Acceleration as a result of Undesired Regeneration Events

Compared to the 2006 competition numbers, this improvement, the hybrid system would have been responsible for as much as a 3.26% improvement in the economy of the vehicle. With the wide range in engine efficiency, it would have been possible for this improvement to be quite higher. The 2006 results, however, were possibly low due to the erroneous ambient temperature data. This seemed likely when the improvement was compared with the previous calculation of the conservatively estimated energy usage based on the calculated capability of the hybrid system. The excess seemed a reasonable change based on a default temperature.

Many factors played a role in fuel economy and not all can be accounted for in this analysis of the undesired events. However, it was evident that an improvement was available from the vehicle if the drives were to have operated properly throughout the event.

ESS Efficiency

The ultracapacitors used by WVU followed the efficiency curve shown in Figure 11. This curve showed the efficiency of the pack as current was applied to or removed from it. The current measured at the motor drives and the energy in the pack based on the change in bus voltage over the same period was compared. This determined the efficiency of the ESS. Over the entire cycle, the ESS demonstrated an average efficiency of 93% over all of the regeneration events. During the undesired regeneration events above, the capacitors demonstrated an efficiency of 81.71%. During these periods, the currents passed into the pack were between 100 and 400 amps or 10 to 40% of the pack's power capability. The drive operated at approximately 400 amps during the first portion of the event while it operated at approximately 100 amps for the remainder of the event. Significant error was found in most of the transient operation between the current sensors and the current calculated using the ESS Voltage. The current sensors had a noticeable delay and also seemed to exhibit diffusion in the data with respect to time. Although detailed models of capacitors showed that the voltage of a capacitor did not follow the typical theoretical model, so what appeared to be delay and diffusion could have also been overshoot on the part of the capacitors [13]. Reality was somewhere in the middle. Figure 27 shows the measured current versus the current calculated from ESS voltage that has been smoothed by a 4 point running average. Figure 28 shows the same with a small time shift found by correlating the two data sets. The R^2 value increased significantly with this correlation. Figure 29 shows the previous data, correlated and smoothed using a running average.

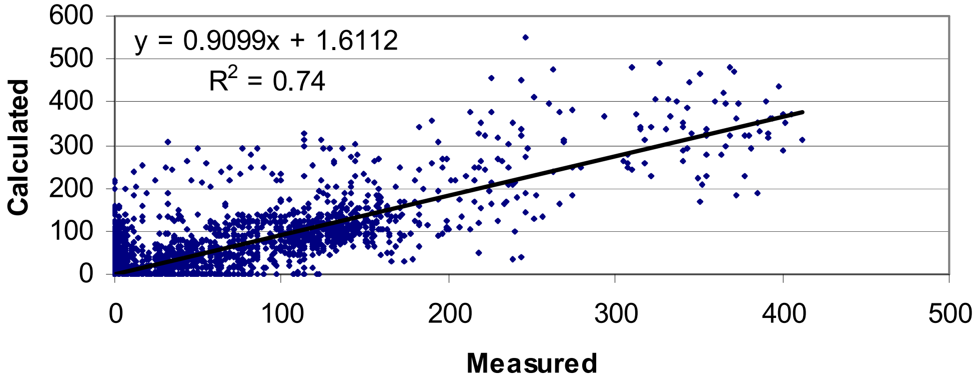


Figure 27: Current Sensor vs. Current Calculated from ESS Voltage

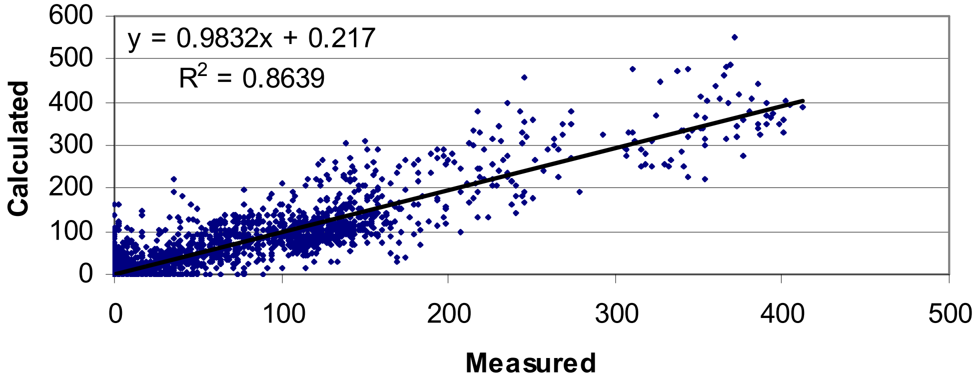


Figure 28: Correlation of Corrected Current Sensor Data vs. Calculated Current

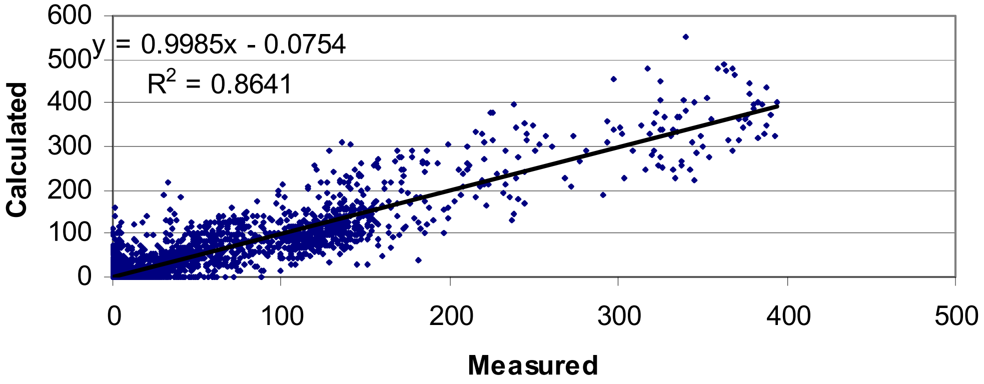


Figure 29: Correlated and Running Average Smoothed Current Sensor Data vs. Calculated Current

Energy Required versus Pack Energy

The WVU ESS was capable of storing usefully 0.17 kWh of energy. The entire cycle required 15.26 kWh. The ESS was therefore capable of storing 1.11% of the energy for this cycle.

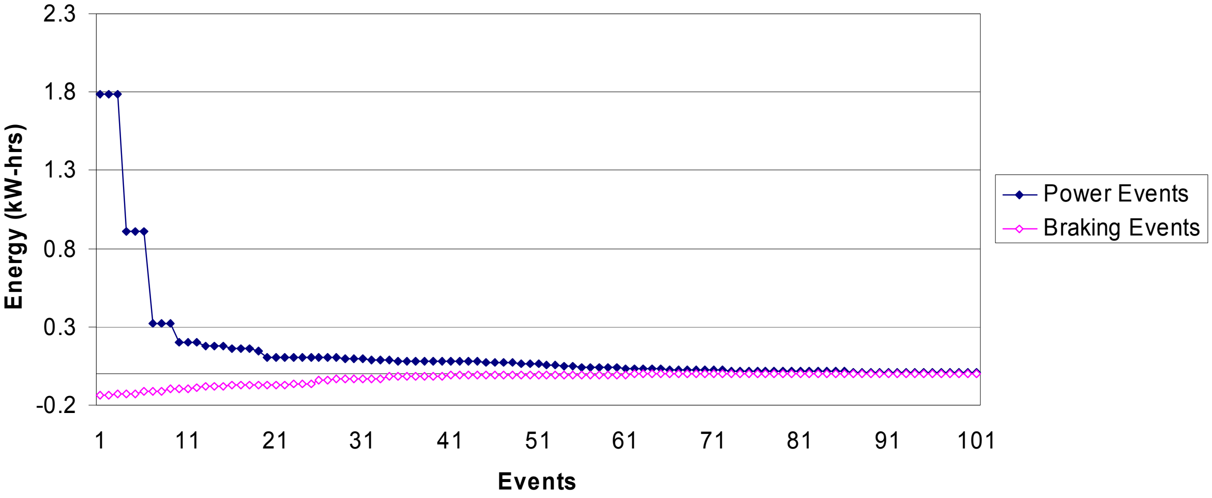


Figure 30: Energy per Event sorted by Magnitude

If the power required to propel and stop the vehicle was divided into events based on the change from propulsion to braking, and the energy required for each event was calculated, the energy for each event can then be sorted. The sorted energy values indicate how often each quantity of energy will have to be handled by the energy storage system. The figure above shows the largest 101 events of the 1001 events for both power and braking derived from the competition cycle. The energy for regenerative events never surpassed 0.14 kWh for each event, indicating that the capacity of the pack at 0.17 kWh was sufficient at least to capture each braking event in the cycle.

Only nine of the propulsion events exceeded the energy capacity of the ESS. Since the energy required to propel the vehicle over any cycle far exceeded the energy captured, this shortcoming mattered little.

The energy stored by the pack was different from the energy available to be captured at the road, 2.85 kWh. Primarily, the losses between the road and the Energy Storage System were caused by the capturing device and its controller. The losses associated with these two items were approximately 10%. So, 2.6 kWh of energy could have reached the pack during the cycle. However, this energy could not have made it into the ESS, since the ESS was only 80% efficient. 2.05 kWh of that energy could have been stored in the pack, which would have lead to a minimum of 12 full cycles of the pack's useful capacity to use that energy.

Pack Size Analysis

The pack was sufficient to capture all braking events for the competition cycle. That is not to say that it could have handled every cycle. Since this was an analysis of event based capability, it seemed that the pack would be capable of handling any reasonable set of events. Decreasing the size of the pack by 20% would have reduced the capacitance to 469.5 farads. That reduction corresponded to removing one string of capacitors. For the competition cycle, the entire energy from only two events was unavailable for capture. However 98% of the energy in those events was still available for capture and the energy lost was 0.0034 kWh and only comprised 0.1% of the energy available for capture in the whole competition cycle. Any increase in size could not have benefited the vehicle for this cycle in terms of its ability to capture the energy from any given braking event. Additional capacity meant, however, an increase in the ability of the ESS to capture the energy at the rate that the vehicle would produce it.

An increase in pack size of 20% or 6 rows of capacitors in parallel, would yield 704.3 farads. Some marginal benefit might have been gained through an increase in efficiency of the capacitors, however nothing that could have outweighed the weight and volume penalty of such an increase. If the motors were enlarged, in order to capture all of the events for the cycle, at some point the physical limit of the capacitors would have dictated some increase in pack size. A 20% increase would have added another 200 amp current capacity to the pack. The total power consumption capability of the pack would have been 1200 amps or 67.2 kW at rated voltage.

Energy Required versus Integrated Motor Power

Figure 31 and Figure 32 show the required cycle energy as in the first figure and the capability of the hybrid motors that corresponded to the same conditions. Figure 31 showed the largest events and Figure 32 showed the next 100 points. The apparently sporadic behavior of the motors was a result of speed-based nature of the motor's power curve.

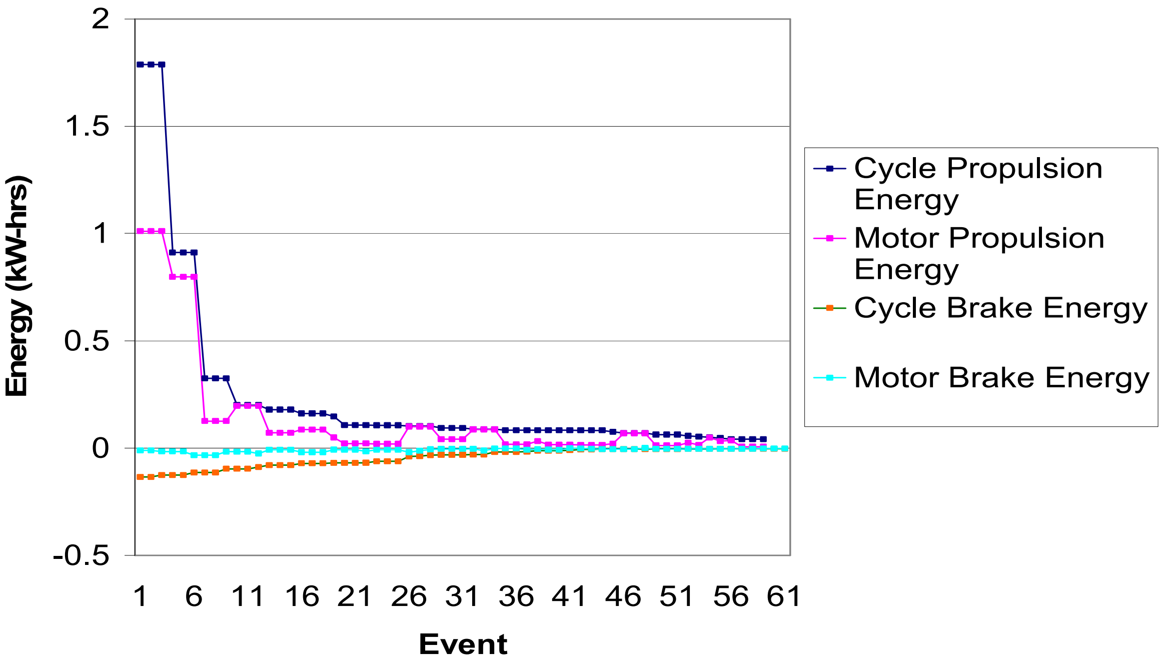


Figure 31: Cycle and Motor Energy Events 1 through 50

Figure 32 denoted a point at which the motors were able to capture the all of the energy of the required braking. In Figure 31, the braking energy of the vehicle was significantly greater than the energy the hybrid system had the ability to capture. This was a result of the braking power capability of the vehicle. The total energy was less than that originally supplied to the vehicle, however, it was removed at a much higher rate and allowed less time for the electric motors to capture it.

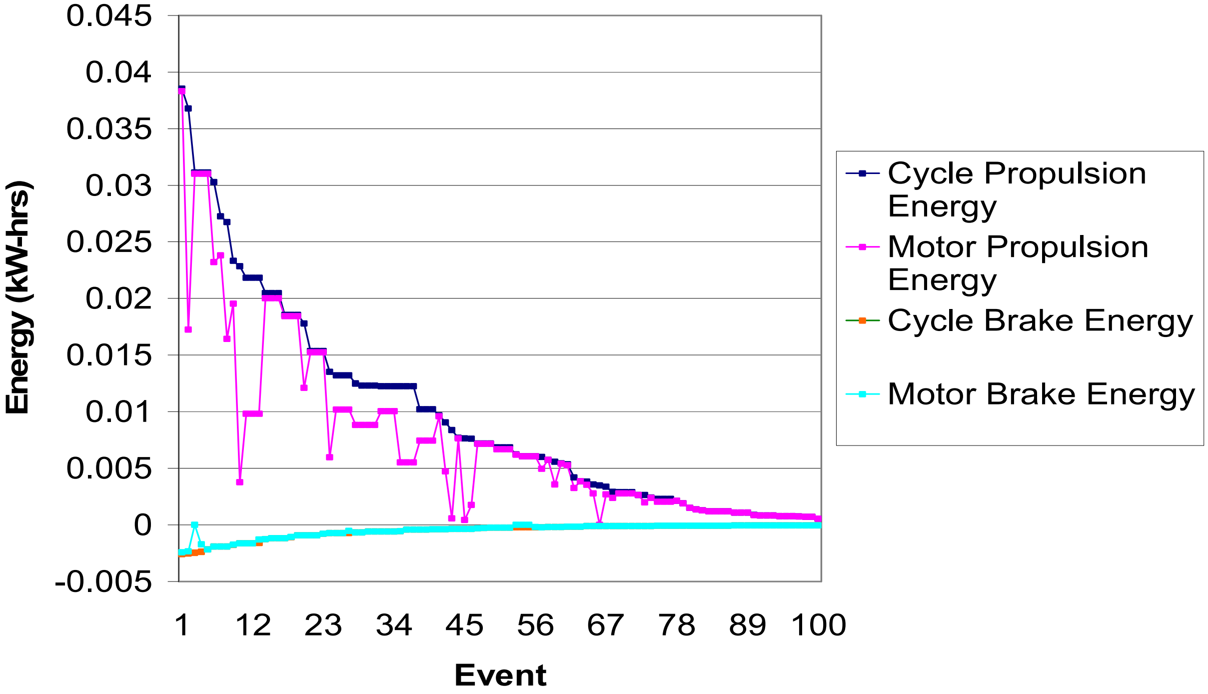


Figure 32: Cycle and Motor Energy Events 50 through 150

Figure 33 shows the events that remained. Notice the distribution of events with total energy primarily above 5 Wh, where braking events were more evenly distributed over the scale of energy content. The remainder of the 1001 events were each less than 0.6 Wh of energy.

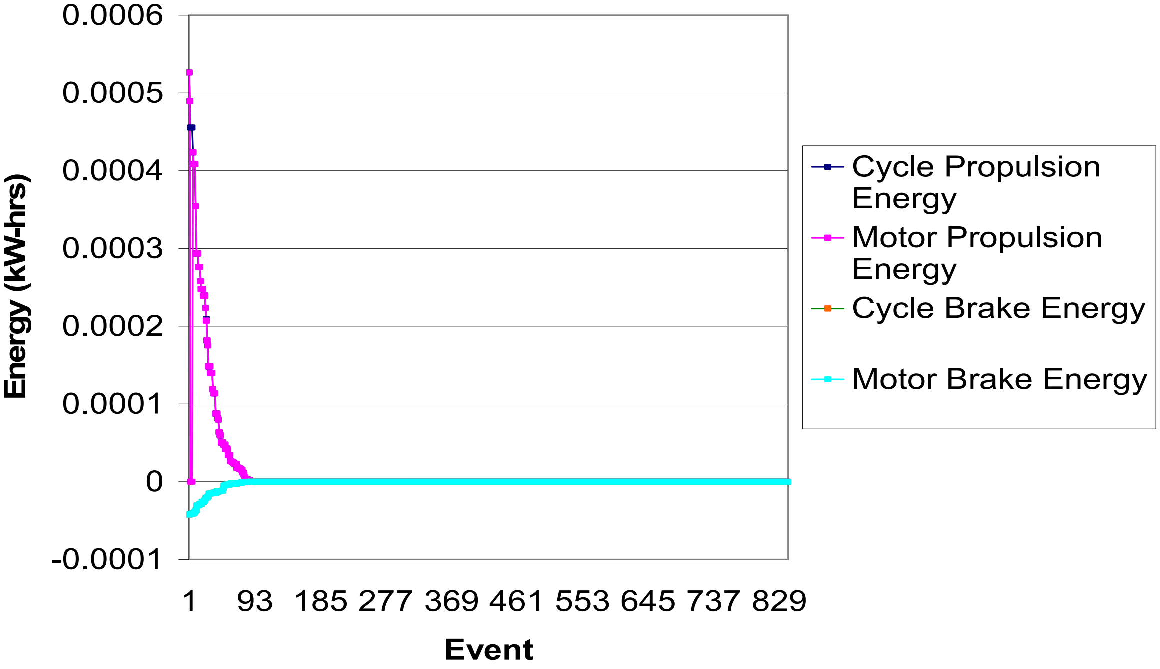


Figure 33: Remaining smaller Events after the first 150

Binned Motor Energy by Speeds

Figure 34 shows the energy the motor was capable of producing or absorbing over the competition cycle. The large spikes at 70 and 50 mph reflected the large portion of time spent at those steady state speeds in the drive cycle. A significant portion of the time representing urban driving was represented in the 35 mph bin. The slope from 35 mph down to 0 was partially a reflection of the limitation of the motor power curve.

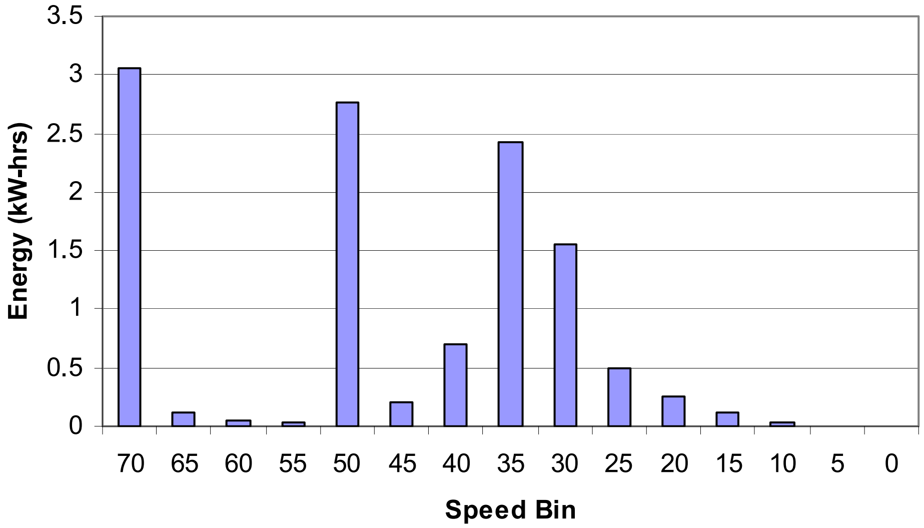


Figure 34: Energy Capability of the Motors over the Cycle by Vehicle Speed

Competition Data

The motor current data taken at competition was the current being generated by the PML motors. In order to display current for both regeneration and power events, the voltage of the capacitor pack was averaged over six data cycles. Then the change in voltage was used to find the energy stored in the capacitor pack.

$$E = \tfrac{1}{2} C V^2$$

Equation (6)

Where C was equal to 585 farads and V was the voltage of the capacitors.

The following equation was used to derive the current, I, at a given time, t, using the change in voltage and the known capacitance, C, of the capacitors.

$$I(t) = c\frac{dV(t)}{dt}$$

Equation (7)

Further, these currents were divided into power and regenerative events. Also, the power multiplied by the time was accumulated to show the total energy used or generated during the driving events. This was compared to the energy calculated by the road load equation for the same speed profile. Also based on the speed data, the power available to be transferred from and to the motors was calculated and the maximum energy that could have been supplied by the hybrid calculated based on the results from the road load equation.

$$P = 0.5C_dA\rho V^3+\mu MgV+MaV$$

Equation (8), from [5]

“Where C_d was the coefficient of drag, A was the frontal area of the vehicle, ρ was the density of the air, V was the velocity of the vehicle, μ was the rolling resistance of the vehicle, g was the acceleration due to gravity, M was the mass of the vehicle, and a was the acceleration of the vehicle.” [5]

The maximum power capable of being produced by the motors is shown in Equation (9).

$$Y = 10.625x - 1062.5$$

Equation (9)

Where Y was the power (kW) of one motor and x was the speed (rpm) of the motor. This showed the maximum capability for the motors along the speed profile for the vehicle. Power profile for the motors was then compared w/ the road load power and a maximum power profile for the motors based on the drive cycle was derived. The actual motor power was derived from the current determined from the ESS Voltage change. This actual power was compared with the power capabilities based on the road load equation and the limitations of the motors.

Figure 35 shows the actual speed profile of one cycle of the entire driving cycle. The road load was calculated from these data. The profile followed is shown in Figure 21.

For the same portion of the data shown in Figure 35, the maximum capabilities of the hybrid motors are shown in Figure 36. Of course the ability of the motors was based on speed, so at higher speeds the graph shows larger motor power capabilities. Both the power capability of the motors, based solely on the speed of the vehicle, and the power that could be used based on the calculated road load are shown.

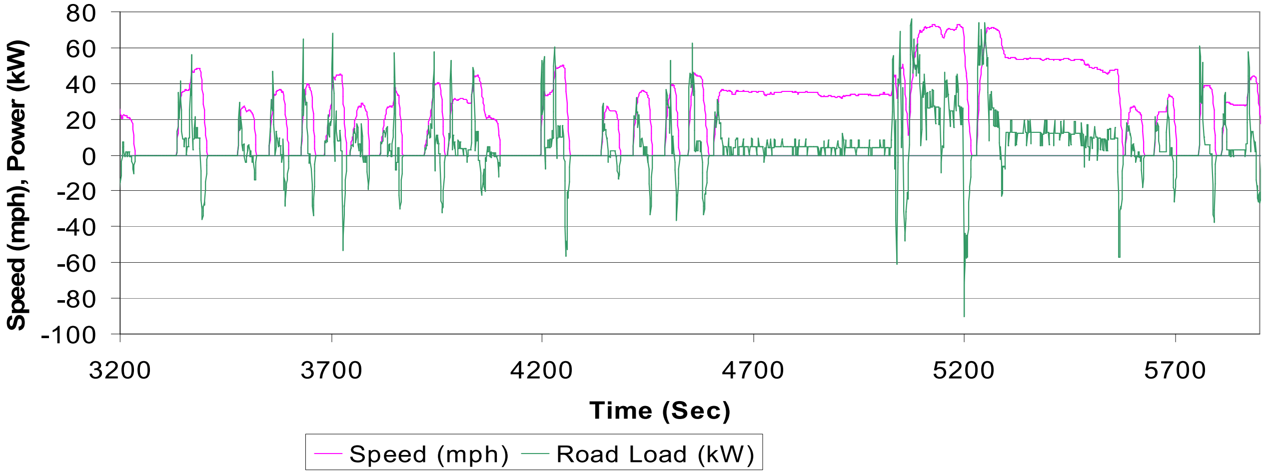


Figure 35: Speed Profile of Competition Drive Cycle with Calculated Road Load

The motors were capable of providing a significant portion of the road load (RL) power required to propel the vehicle as shown in Figure 36. Unfortunately, the braking events were not as much within the capabilities of the motors since these events tended to be shorter than power events.

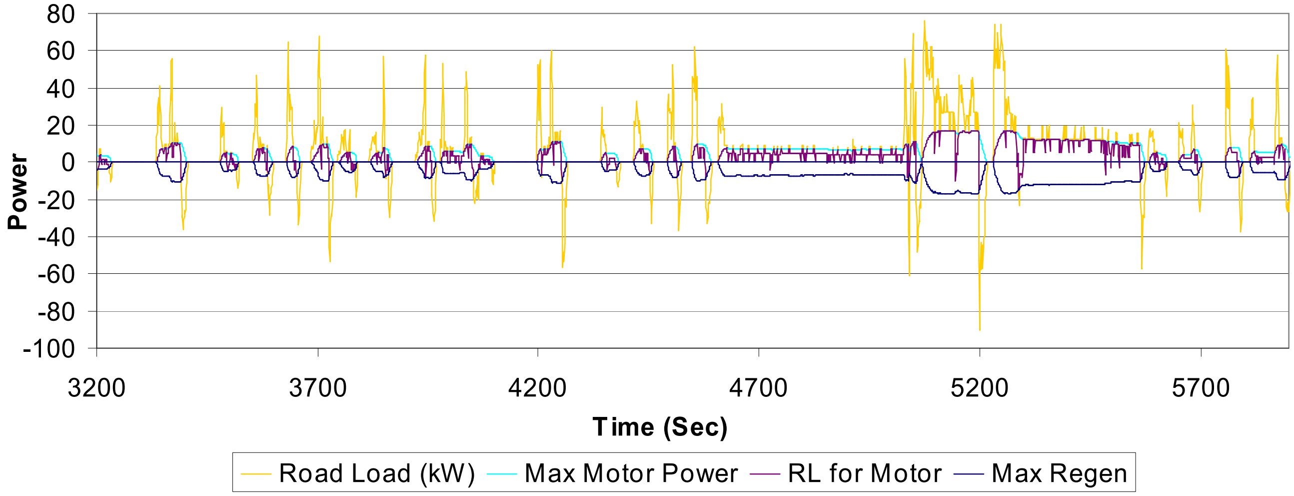


Figure 36: Motor Capability compared to Vehicle Power Requirements for Competition Drive Cycle

A small portion of the data shown in Figure 36 is shown in Figure 37 to clarify the limitation of the motors to supply the required energy as well as capture the energy lost through braking. Small events could have been almost completely handled by the motors, where as the larger events of peak load could have only been assisted by the motors.

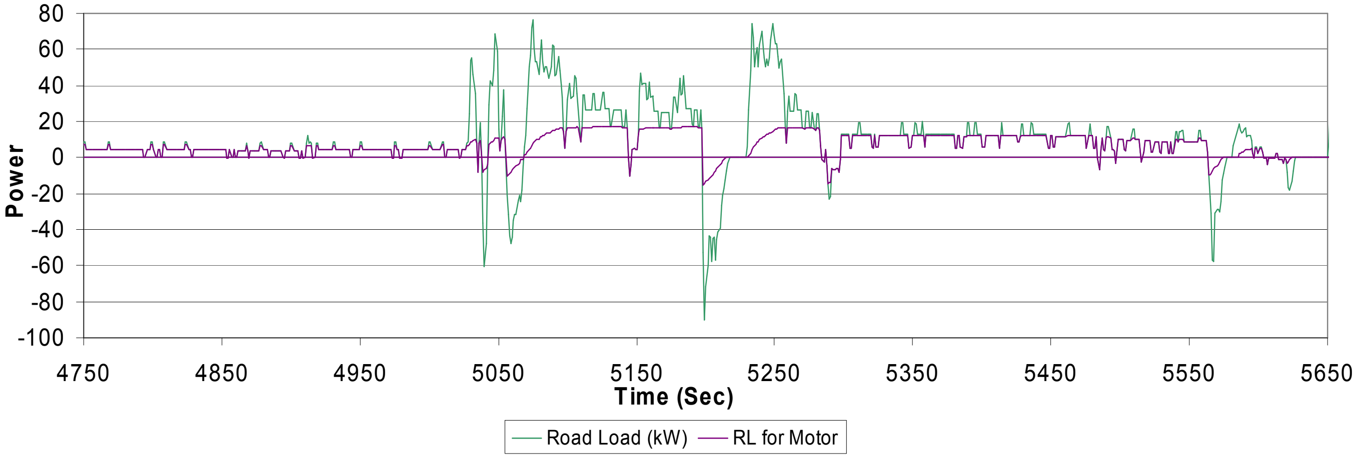


Figure 37: Road Load compared to the Capability of the Motors

The actual performance of the motors is shown in Figure 38. For perspective, the maximum power of the motors and the road load limited to the motor power is also shown. The power output was limited by the ability of the motors to recapture braking energy.

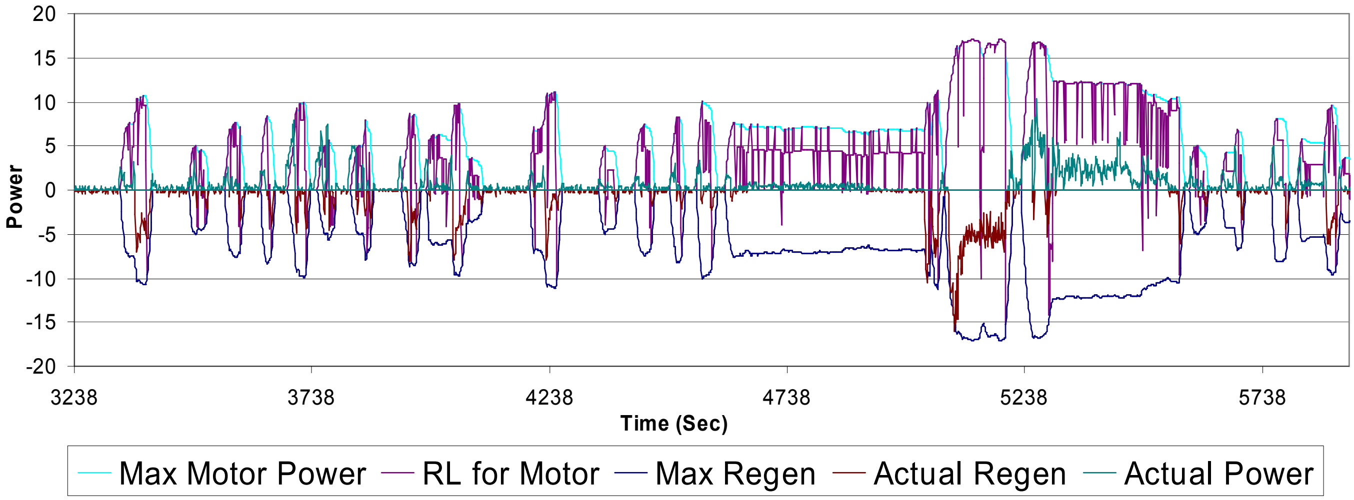


Figure 38: Maximum Capability of Motors given Speed with RL and Actual Power as driven

Figure 39 shows a portion of the motor data during the low speed city driving section of the cycle. Notice that regeneration was consistently similar to road load while the motors powered the vehicle at variable power levels depending on the control strategy. Figure 40 shows the highway portion of the cycle at a similar scale. Again, the regeneration was consistent while the proportion of road load power from the motors varied widely.

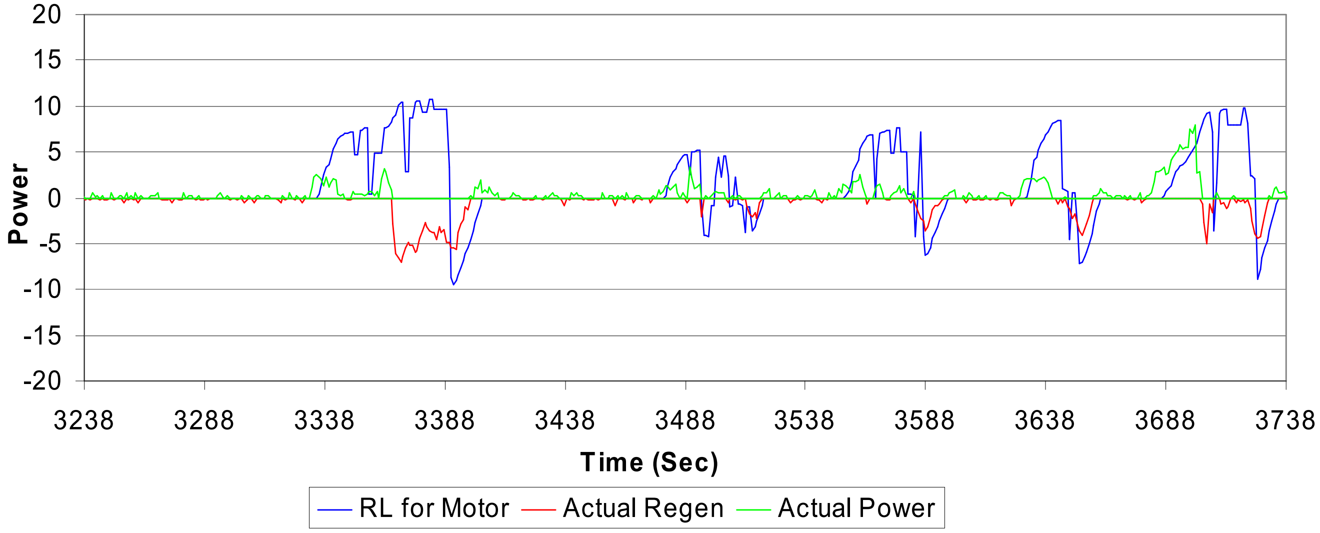


Figure 39: Motor RL compared to Actual Performance, Low-Speed Profile

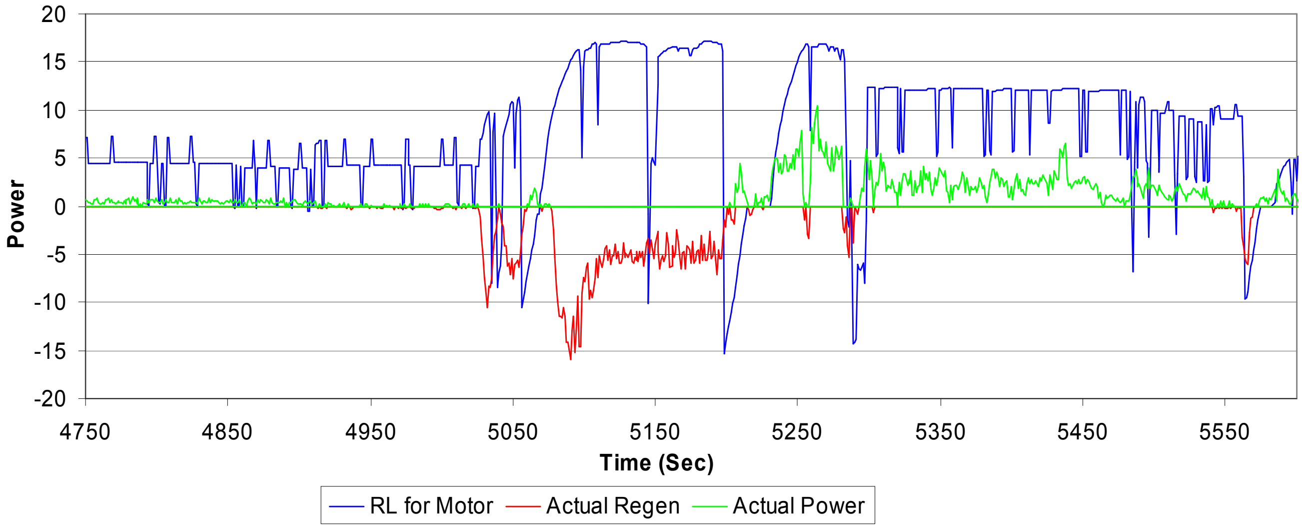


Figure 40: Motor Road Load compared to Actual Performance, High-Speed Portion of Profile

If the energy used by the vehicle was calculated based on the road load equation and the energy available in the fuel were compared, the vehicle had 12.08% efficiency over the fuel economy course.

If fueling while the car was idling were removed, the efficiency would have been 13.74%. This assumed an idle fuel rate of 4.29 pounds per hour. This value was taken from actual engine data with accessories such as the water pump and alternator, but without air conditioning. The time at zero speed was multiplied by this number and subtracted from the amount of fuel used at competition. Unless a strategy was adopted where the engine were off at idle conditions, this was only useful for comparing the energy used while driving to the energy calculated using the road load equation.

Conclusions and Recommendations

The original intent of the control strategy and the indeed the whole hybrid system was to maximize the regenerative energy captured. While this strategy did accomplish this goal, it did not provide the best strategy for using it.

Also, the key parameter in this strategy was the mythical amount of energy capable of being recaptured given the vehicle's current speed. More realistic curves were explained above and perhaps some statistical analysis or active artificial intelligence could have been applied here to more accurately reflect the energy capable of being stored.

Fuel Economy

In 2006, the WVU Equinox proved to be 20% more fuel efficient than the stock vehicle without a functioning hybrid system. This improvement was based solely on the diesel powertrain performance. Both the efficiency of the diesel engine and the downsized powertrain played a part in this improvement. In 2007, it proved to be 18% more efficient with the hybrid system functioning as described above. Through some post processing, the unintended events were accounted for in a conservative manner and an improvement over stock of 23% was calculated. The vehicle likely provided much more benefit without the motor regeneration problem, as this post processing did not take into account all of the losses and used a generously high engine efficiency.

The improvement produced by a hybrid system could have been greater with a gasoline engine than a diesel engine because the gasoline engine would have provided more opportunity for improvement in fuel efficiency.

Selection and Design of Control Strategy

The use of an ESS with high power density and low energy density necessitated a different strategy based more on the energy storage limitations of the ESS than the power limitations of it as with the usual electrochemical storage means. With most conventional storage media, the limitation when regenerating is not the capacity but the rate at which they can be charged. With a larger storage capacity, many regenerative events can be stored in a row and not exceed the capacity of the ESS, however, with the ESS sized on the same order of magnitude as possible regenerative events, it is much more likely that an event would be missed or only partially captured due to a lack of capacity. A dual storage system could eliminate this issue by increasing energy storage. The system would be less efficient though because of a second transfer from capacitors to batteries. Additionally, the ESS sizing calculations above show that the WVU pack would not benefit from additional storage on a per event basis. The benefit would only be in a more flexible energy usage strategy.

Examination of Performance

The ESS was capable of capturing virtually all of the energy, but was limited to a 50 kW input rate as configured. As originally designed, motors capable of 40 kW could have captured all of the energy from over 75% of the braking events, however, severe limitation of current (down from 800 to 280 amps) also limited the usefulness of the hybrid system. With a current limitation of 200 amps, over the cycle, the motors were capable of recapturing 6.65% of the energy from the cycle, and system inefficiencies reduced the capability of the system to reduce the fuel required to power the vehicle to 3.4%. These numbers were found by comparing the sum of the event energies for the cycle propulsion with the energy that was recoverable with the motors and the theoretical efficiency of the hybrid system in returning that energy to the road to reduce fuel consumption.

Proposed Architecture and Control Strategy Changes

The switch to a diesel engine produced a substantial increase in fuel economy. In year two, a 20% improvement in fuel economy was realized without the benefit of the hybrid system.

The hybrid system provided a modest benefit to the vehicle's fuel economy and could provide much greater improvements if refined further. The motor and controllers used were clearly designed for all electric vehicles and not intended for use in a more intermittent duty as in a hybrid vehicle. This caused several problems in controlling them and adapting them to the vehicle. The motor controllers limited the hybrid performance greatly in many ways:

1. The torque supplied by the controller to the motors was proportional to the speed of the motor, not as shown before purchase. It appears peak usage was not well defined within the controllers rather than thermal management being the issue.
2. A liquid cooling system could have enhanced the motor controllers. This addition would have allowed greater motor current and further fulfilled the capabilities of those motors both in powering the vehicle and in capturing regenerative energy.
3. The malfunction that caused the motor to regenerate at higher speeds continuously could be eliminated, allowing the system to function properly.

The existing control strategy performed as expected in terms of maintaining head room in the ESS. Its effectiveness would be more evident with larger motor capacity. The mismatch in the ability of the motors and the capacity of the ESS showed that this strategy was not as effective with an ESS that was larger than that necessary to capture one maximum event. By itself, this strategy, would not be well suited for a vehicle using a battery ESS. If a separate strategy were used in conjunction that used stored energy based on engine efficiency, it would have prevented the stored energy from trickling out of the ESS.

Further analysis could yield a desired SOC map that would better balance the energy likely to be stored in the next event with the energy that could possibly be stored. The curves above show that an increase in the desired SOC over the speed range would allow more energy to be stored until it is most beneficial to use it. A statistical analysis of the losses associated with further increases over the driving cycle may yield a more reasonable map.

Some basic calculations of the fuel used during the fuel economy testing at competition showed that a 16% improvement in fuel economy could have been gained if the engine were shut off when normally at idle. Several technical challenges would have to be over come before the engine could be shut off and again started properly to realize this projected gain. The transmission would have to be modified so that fluid would still be circulating, the 12-volt system, and the AC would still have to work regardless of engine function. Also, starting the engine fast enough would be difficult for several reasons including power required, belt tension, and ECU problems. These difficulties may or may not make this improvement out of reach for the WVU Challenge X project.

If the motor controllers were capable of managing 400 amps of current each, the improvement in fuel economy would increase significantly, so an economy improvement of 25 to 26% seems within reach with the originally designed system.

If the control strategy were to be improved upon, the energy stored could be used to reduce fuel consumption when the vehicle is most inefficient rather than proportionally during all events. This would lead to a greater benefit using the same captured energy. With the strategy used at competition, the energy was used most under the highest load where the engine was probably most efficient. If the energy were used when the engine was least efficient, a significant improvement would result.

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