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Ultracapacitor Sizing and Packaging For Cost Effective Micro-Hybrids

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1 - ABSTRACT

Ultracapacitor energy storage systems (ESS) offer the highest return on investment, the best performance and the highest safety ratings of any ESS available on the market today. Ultracapacitors also are the most cost effective solution for power applications available today. Automotive OEMs are challenged with meeting significant CAFE[1] standard improvements and no single technology offers more promise as a cost effective and reliable solution than ultracapacitors in micro and mild hybrid applications than ultracapacitors. However, major automotive OEMs and ultracapacitor suppliers are struggling to find a working relationship that promotes use of ultracapacitors in micro and mild hybrid applications.

This paper and included research examines the costs, both current and anticipated, of the various ESS systems available to the OEMs and their engineers today. Given the standard development times and the increase in production that would be required to meet the tremendous demands of the automotive market, the time is now to begin the development of an optimized hybrid battery system for micro-hybrids. The financial model discussed in this paper and nearly all the published literature agree that the future of starting systems in automobiles is ultracapacitor-based.

2 - INTRODUCTION

Many countries now have taxes and incentives in place designed to encourage consumers and manufacturers to purchase and provide automobiles that offer a higher fuel efficiency [4]. OEMs worldwide have been looking for cost effective solutions that improve fuel efficiency while maintaining or improving performance and meeting the levels of luxury and appointment that customers are accustomed to. European consumers will not accept cars that cannot travel at autobahn speeds [4] and Americans will not accept cars where the air conditioning stops working or the lights dim while waiting at a red light. As such, there are many considerations when making changes to how a car fundamentally operates from both the engineering and marketing perspectives.

Although there are many hybrid vehicles on the road today, there is not a consensus between OEMs and ultracapacitor manufacturers over how to hybridize the remainder of the automotive fleet. Sales of hybrid cars, other than the Prius, have been below expectations, though data indicates continued growth. While most attribute the sale of the Prius to rising gas prices, the reality is that plug-in electric vehicles and electric vehicles remain status symbols, purchased primarily by those who make on average $195,000 p/a.

Major OEMs must consider many factors beyond current market demographics, most importantly market share and profitability, when exploring hybridization options. It is important to note that these electric vehicles are often subsidized by governments working to improve their carbon footprints, as well as by the OEMs themselves. Thus, the fact that the electric vehicle technology is most popular among those who are able to afford the vehicle without the subsidy does not have a positive effect on the company's profitability and market share. The Prius, while a highly efficient car, does not meet everyone's needs. It is not inexpensive to manufacture or to purchase, and the technologies that make it economically attractive from a long-term perspective are expensive up front. For example, the technology it currently incorporates has known wear out mechanisms that drastically increase the long-term cost of ownership. The battery needs replacing after five to seven years of normal service (after fewer than two years in vehicles serving as taxis), and can cost more than $7,000 to replace [6]. In contrast, the widely accepted standard among automotive OEMs is that a battery should last 10 years [4] and currently, OEMs are working to change the life requirements for high cost components in a vehicle to 15 years. The bottom line is that OEMs must make vehicles that are not only more efficient, but also more reliable, with a lower total cost of ownership, and incorporate in amenities that make them more desirable.

The clearest way forward to improve on the fuel economy of vehicles while maintaining other marketable attributes appears to be installing start-stop systems, also known as micro-hybrids. Micro-hybrids (MHV) are, as the name suggests, the smallest step from traditional vehicles towards full hybrid vehicles. They include a start-stop feature that stops the motor from operating when the car is at a complete stop, and then restarts the motor when the driver moves again. There are several variations of this technology; some systems use the starter or alternator to charge the auxiliary ESS, which is used to provide power to devices during the stop event and when restarting the vehicle. The most basic MHV only shuts off the engine when the vehicle is stopped and restarts it when the brake is released. These variations of micro-hybrid vehicles are part of a larger portion of the vehicle market referred to as "High Efficiency Power train" (HEP) vehicles.

In theory, a start/stop system is a simple improvement and the cost to add it to a vehicle is low. The system can improve overall fuel efficiency by up to 10% (for heavy city driving). However, the actual integration of this feature has proved daunting, as adding this feature can be a complex and costly process. Auto OEMs are required to improve vehicles' software to ensure that the motor starts at the right time and smoothly; to add increased safety features that will enable the car to start from the drive position; and to improve the ESS for better support of the accessory electrical loads while the vehicle is off.

The existing battery-based ESS systems have proven to be one of the largest problems [9] for auto OEMs today. The existing lead acid battery or its direct replacement all have enough power and energy to easily do the job that is required of the ESS, but these batteries cannot absorb charge fast enough to recover from one event to the next. In addition, lead acid chemistry rapidly breaks down when not kept at full charge [7]. Even when manufacturers have installed multiple batteries, the results remain the same: the chemistry cannot hold up to the application for the required life [9]. In addition, at temperatures less than +3 degrees Celsius, most manufacturers disable the stop/start system because it is too hard on the batteries to operate below that temperature. Thus, an automobile is toting around at least 50 pounds of unnecessary weight while the system is off, or using a battery that cost 4-5 times a standard battery and that provides no additional benefit.

In light of the duty cycle required a standard test has been developed to cycle the batteries repeatedly in a similar fashion to how they would be cycled in vehicles. The test is called EN-50342-6. This test was conceptualized developed and validated by BMW, Ford and Moll. The current choice product for existing production vehicles is AGM batteries. Although it is much more expensive to produce than a Standard SLI, it is less sensitive to cycling and has similar power capability.

While several technologies have a number of attributes necessary to meet the requirements of the MHV application, none seem to have all of them. One solution is to combine an energy-rich technology with a power-rich technology to help the automotive industry to meet the increasing standards and to rapidly advance the fuel economy of many of its vehicles. Ultimately, using this combination technology will lead to vehicles with fuel efficiency improvements of more than 50 percent.

3 - LITERATURE REVIEW

The research in this area has been focused on the use of individual technologies, though many of the authors suggest a hybrid energy storage system is the best solution [4]. However in completing the analysis, several articles detail the problem facing auto OEMs today succinctly. To begin with, we will look at the four functions the battery must handle in a MHV [4]:

- Engine Start Stop
- Charge Voltage Control
- Regeneration Braking
- Passive Boost

Regeneration braking requires partial state of charge (PSOC) operation [5] and will generate energy. This function requires the ESS to have the ability to absorb that energy. In

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simple terms, the battery cannot be fully charged if it is expected to accept charge from the regenerative braking system. Lead acid batteries, as well as most battery technologies, are only really good at quickly absorbing energy in a very strict state of circumstances, primarily when they are at a reduced state of charge (SOC) and within a specific temperature range. Traditional starting batteries (SLI) are typically thin plate designs, which only work well at high SOC.

However, other lead acid chemistries, like sealed lead acid, often referred to as absorbed glass mat (AGM) batteries, do much better in the regenerative braking process because they do not suffer from stratified acid [5], which commonly affects batteries kept at low charge. However, AGM batteries cost 4-6 times the cost of an SLI and do not achieve the required life cycle and are not reliable at colder temperatures. Other technologies are better at meeting the life cycle and temperature requirements, but are also more expensive than lead acid batteries and must be sized to allow for the PSOC [9] operation, which requires bigger systems and an increase in cost, and also presents new safety hazards.

Figure 3.1: Historic and Projected Cost of Lead

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In order to facilitate rapid integration of technologies to meet these requirements and to reduce the cost of commonly required technology, the United States Automotive Battery Counsel (USABC) was put together by the major North American OEMs. This organization has jointly documented OEMs' findings and made them available to the public in order to facilitate potential ESS suppliers' understanding of the requirements. The key details are considered general enough to cover the non-commercial automotive market and the commercial market up to class 3 vehicles for most applications. Those details are as follows:

- Power Pulse up to 6kW
- Cranks capacity: 3 events of 4.5 kW*4.5 seconds in less than 30 seconds
- Sustained voltage 14.6V
- Passive minimum voltage under crank criteria 8.0V
- 15 year calendar life at 30C (500,000 cycle)
- Available energy 360 Whr (30Ahr)
- Operating temperature range -30C to 75C (52C not under hood)
- Max weight 10kg
- Max volume 7L
- Max cost at volume in excess of 100k/year $220

Figure 3.2: Historic Cost of Capacitance EDLC

In nearly all areas of these criteria, ultracapacitors (EDLCs) are superior to all other battery chemistries for the automotive applications [3]. The following list represents where ultracapacitors are superior:

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- Volumetric and gravimetric power density superior to all battery chemistries
- No sensitivity to depth of discharge cycling
- Limited sensitivity to cycle rate
- Calendar life and cycle life superiority
- Nearly no capacity loss or ESR Gain in the temperature range required

Areas where EDLCs fall short of meeting the standard (USABC) independently:

- Max weight significantly exceeds 10kg to meet 360Whr energy storage (>100kg)
- Max Volume significantly exceeds 10kg to meet 360Whr energy storage (>100L)
- Max cost at volume in excess of 100k/year would still exceed $10k at 360Whr

Notice that each one of the areas of failure relates to energy density. When doing a comparable analysis of each of the other technologies, they would fail in relationship to power density [3]. In his research, Eckhard mentions that a combination of an EDLC with an energy dense battery likely would yield the best possible results, noting, however, that capacitors need to achieve a cost of $0.003/F [4] in order for this to be a viable solution. Evaluating the costs in Professor Burke's analysis shows that the costs of ultracapacitors are rapidly approaching that number, while lead costs and the costs of other technologies are growing past the anticipated price levels [3].

Figure 3.1 and Figure 3.2 show a cost comparison of the cost of lead vs. the cost of capacitance (based on EDLC capacitors). The cost of lead has grown significantly over the past decade and is projected to continue to grow, while the price of capacitance has dropped over approximately the same time period. While this doesn't necessarily correlate directly to the end cost of the system, it is a good indicator that reducing the lead and increasing the capacitance of a power and energy system may be a good idea for cost in this type of hybrid ESS.

4 - SYSTEM DESCRIPTION

The system as it exists today uses either one or two energy storage devices as a means of integration between the ESS and the vehicle. Commercially used energy storage devices include lead acid batteries (SLI and AGM), supercapacitors (EDLCs) and lithium ion batteries. Some other advanced hybrids may use nickel metal hydride batteries, but not in the market we are considering. When determining which combination of energy storage systems to use, one must also consider the proposed location in the vehicle.

Because this hybrid system requires multifaceted optimization, there may be several goals

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or considerations in the vehicle design that limit the energy storage system used to particular size or capacity. As a general rule, the electrical loads in vehicles are ever-increasing [4] and much of that increase is intended to reduce the fuel consumption, done through moving mechanical or hydraulic systems onto the electrical bus. This generally reduces the average load on the engine because this design enables systems to only run when it is required to, rather than constantly. Many OEMs have already moved several features standard to cars, including cooling fans, power steering, brakes and fuel pumps, to the electrical bus. OEMs must take into account the level of power required by these systems, as well as the alternator's ability to support them, when determining which ESS to use. Another key factor in determining the size of the battery is the potential energy consumption while the vehicle is off. For example, 30 days of a minimal load on the ESS requires 360 watt hours. As a general rule, automotive engineers have refrained from putting any load on a starting battery during the operation of vehicles, and most often, the alternator is required to handle all loads in normal operation.

The addition of regenerative and acceleration assist devices are a large departure from historical uses [11] of starting batteries, and is a largely unknown territory for many OEMs. More advanced hybrid cars do not use starting batteries [12] for energy storage as the technology enables the vehicle to have large energy reserves on board which can be used to start the motor as needed.

However, these advanced hybrid cars still have a 12V [12] bus that supports the management of the vehicle and other systems, all of which have been carried over from non-hybrid architectures, including windshield wipers, gages, and power windows. The large ESS on board supports the engine-off function for start-stop operations in mild or full hybrids. In a brief evaluation of a vehicle electrical system, ELDCs can handle all of the surge power requirements and the starting of the vehicle better than any battery technology because in these processes, the power requirement is high and the energy requirement is low. However, the key-off energy consumption cannot be managed by a small bank of capacitors, so this is where the battery is important. While the USABC specifications only require a 30Ahr battery, most vehicles use 75-90Ahr batteries to meet the auto stop energy requirements.

In Europe, several auto manufacturers have started to sell cars with an EDLC system. This system switches some bulk capacitance from parallel to in a series with the battery in order to keep bus voltage high for starting events. While this may be an adequate and cost effective solution, it is only a temporary fix for the problem. Because loads are so high, voltage sag is the real problem; energy storage systems must be able to maintain a voltage above 8.0V. Other problems include noisy voltage bus, excessive battery usage and, because all the current still goes through the battery, it breaks down just as quickly as other batteries. Total system cost, including the high tech switch that enables this system to perform, exceeds

$300 and only adds a couple of months to the life of the battery.

All systems currently in use are not long-term solutions, as they either do not last the length of the warranty or do not perform well enough to achieve a long life. A hybrid solution is the right answer to the needs of both OEMs and consumers, and costs are now lining up with system requirements. In addition, the shortcomings of existing systems are now so widely recognized that the perception of acceptable cost has changed and made these systems more affordable and desirable.

5 - TESTING

The predominate ESS for MHV on the market today is AGM battery technology. The accepted method for determining the capability of the technology is the EN-50342-6 test. Figure 5.1 shows the performance of a typical AGM battery built for MHV applications. The results show that while the initial performance is acceptable that performance quickly degrades. The important details of this test are the TOC (Top of Charge) current and the charge time. These demonstrate the batteries ability to recharge (Charge Acceptance) and how long this takes. It is also important to note that the test requires a rest period every 500 cycles. After these rest periods the performance is not acceptable and it takes several cycles to get the battery back into a usable condition. This rest period is similar to parking a car over night. The reality of the application is that the system intelligence on the car would not allow most of those cycles to happen, meaning it the system would only engage the auto shut off a small percentage of the time making the system have very little befit. Additionally in a commercial delivery vehicle or taxi, where this system would have the greatest impact and value, this test only really represents a few days (less than a month) of operation. Clearly the AGM, although much better than typical lead acid batteries is not the right answer.

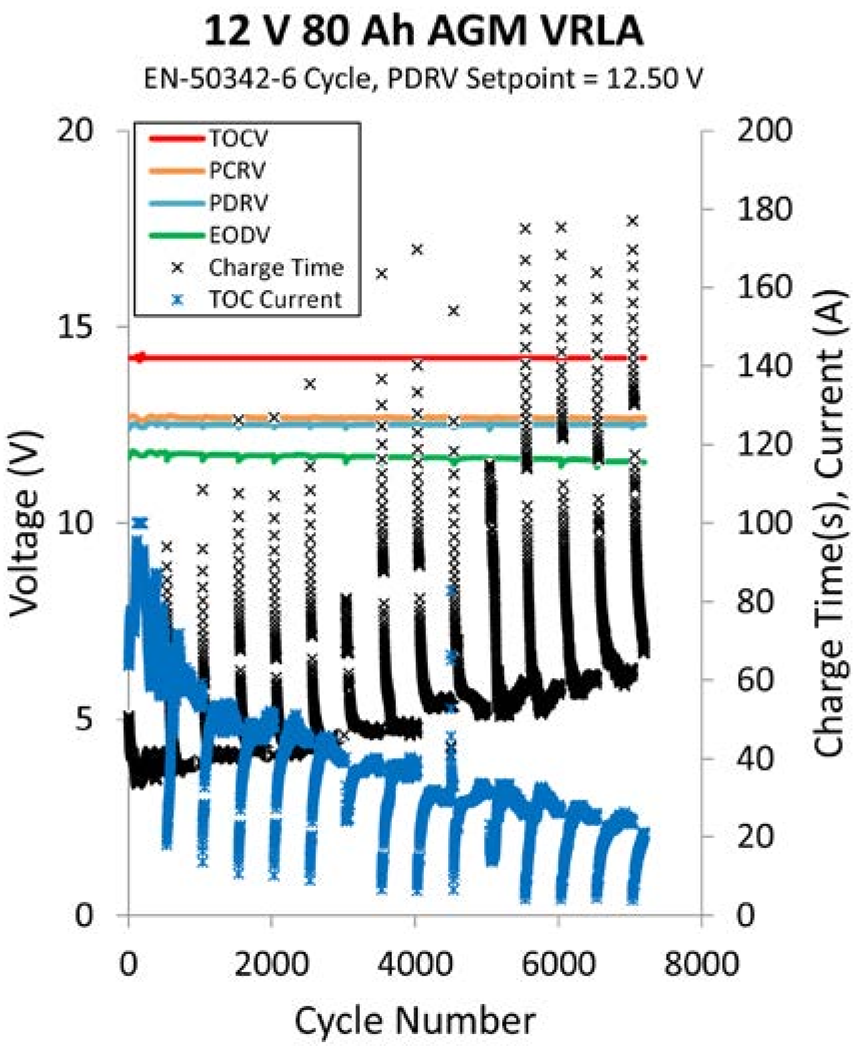

Figure 5.1: AGM EN-50342-6

Figure 5.2 Shows how an EDLC operates under the same conditions. You will note the ultra-capacitors continue to perform as new to 100,000 cycles, this would be expected to exceed 1,000,000 cycles in this application. Note that this test simulates the entire off cycle loads as well as the cranking event. You can see that the performance is superior in every way to an AGM and this test only shows the 25C testing. The perfomance over the entire operating temperature range would be nearly identical for ultracapacitors, the same cannot be said of the AGM chemistry.

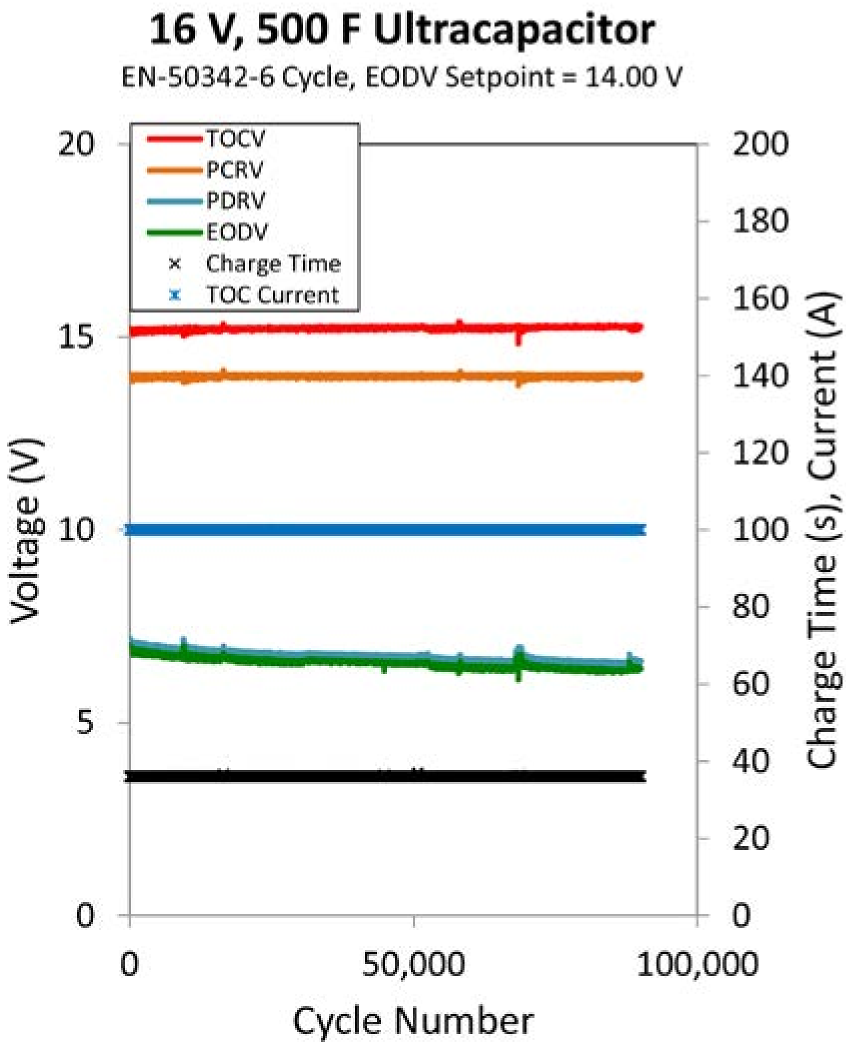

Figure 5.2: Ioxus EDLC performance EN-50342-6

6 - METHODOLOGY

The key driver for change at the OEM level is cost. It has taken governmental fines, dilution of market share, and huge public outcry for manufacturers to even take minor steps toward addressing the issue of fuel economy in vehicles. In fact, as Figure 6.1 shows, the average fuel economy has hardly changed in 30 years. The bottom line is always the dollar. In order to evaluate the integration of any suggested new technology that may solve this problem, an extensive evaluation of the financial impact of such a change is paramount.

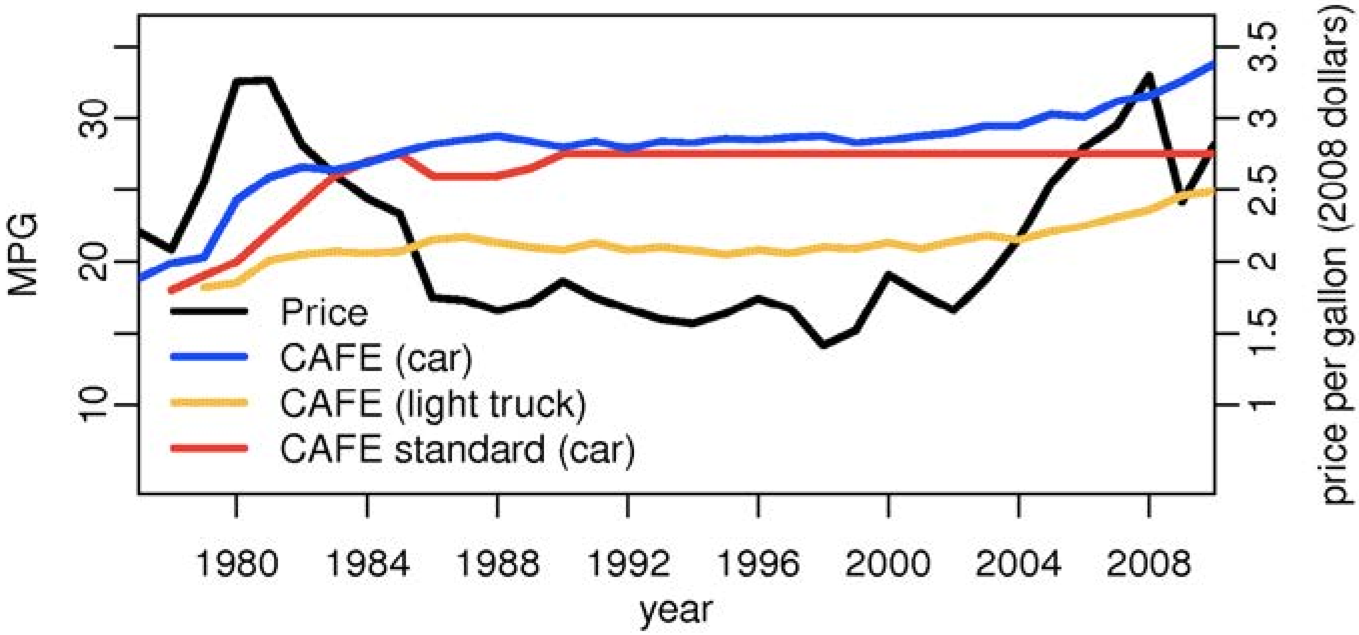

Figure 6.1: Historical CAFE Standards

Two models were developed, each using a different control strategy, to help achieve the largest financial gain either for the OEM or for the end user. The first model used a control strategy that only allowed the stop/start system to work if the battery was at or near 100% SOC. The other allowed for unlimited use of the start stop system, which is unrealistic for batteries.

Figure 6.2: Nominal Recharge time for Stop/Start Events

Chemistry	SLI	2x SLI	AGM	2xAGM	Lithium	Ultracaps
Recharge time for Model 1 (Hr)	0.17	0.08	0.17	0.08	0.07	0.004
Recharge time for Model 2 (Hr)	0.00	0.00	0.00	0.00	0.00	0.000

There are two key concerns for cost in the eyes of the OEM: first is the additional cost to the vehicle bill of materials and the second is the cost of warranty. Both models assume that the warranty is for 3 years, which is the international base standard for automobiles. We are not considering additional safety issues within this model; however, it should be noted that batteries historically have been a source of fire, explosion, flammable gas and other significant forms of failure. Using energy storage systems assumes a host of safety and reliability requirements, so when exploring the cost of a system, one must take into account both integration and lifetime costs. For example, lithium has proven to be very sensitive to charge current and temperature, two factors not regulated in the battery compartments of most vehicles worldwide.

Figure 6.3: Current Component Costs For Auto ESS		
60 Ahr SLI Cost	$	50
60 Ahr AGM Cost	$	110
60 Ahr Lithium Battery Cost	$	500
30 Ahr SLI Cost	$	32
Capacitor Module and Controls	$	325
Capacitor System cost (w/battery)	$	357

Current costs and cost trends are considered in the future cost analysis for each of these technologies. These price trends are one of the key justifications for considering a technology. If the cost to the OEM will be acceptable by the time the product goes into production, it can be considered as a viable option. The typical time line for a development project for a major OEM is approximately 36 months. Current costs are detailed in the 'current costs' Figure 6.3 and the initial costs are considered for production as if it started today.

Figure 6.4: Warranty and Wear-out Considerations

		SLI	2x SLI	AGM	2xAGM	Lithium	Ultracaps
Cycle Life	Cycles	500	500	800	800	1500	500000
Stop Start Cycle depth (nominal)	%	5	2.5	5	2.5	5	50
Warranty	Yr	3	3	3	3	3	3
Maximum Product Life	Yr	5	5	5	5	10	20

Warranty cost considers how each battery wears out, ignored in this calculation is the cost of towing, charging or jump starting. It is assumed that the battery wear out mechanisms can be predicted or detected prior to affecting the customer and thus can be serviced without additional costs. Of course this is unlikely and considered one of the strongly conservative estimating factors of the model.

Figure 6.6: Commuting Scenarios

		Low	Medium	High
Distance Between Stop Start/ events	Miles	0.5	1	10
Average Commute Time	Hr	0.25	0.45	0.75
Average commute distance	Miles	12	22	48
Average Commute Speed	Mph	10	25	65

Another key consideration for the model is the effect on the customer. This can be subjective, so the benefits were limited to fuel economy savings based on miles commuted. Note, this model only considered commuted miles, not miles driven for pleasure or other needs. Engineers at the major OEMs all have different considerations and look at different consumer groups differently; some look at high level users only and some look at the range. The data was conglomerated in the commuter scenarios and the matrix of scenarios Figure 6.5 and probabilities Figure 6.6. Doing this allowed for a mean value for all calculations to simplify the final analysis but also allowed for a look at the range of possibilities.

Figure 6.7: Matrix of Scenarios and Probabilities

Nominal Scenarios (Distance-Dist BTW Stops)	L-L	L-M	L-H	M-L	M-M	M-H	H-L	H-M	H-H
Probability	0.1	0.2	0.05	0.15	0.2	0.025	0.025	0.05	0.2
Number of Stop-Starts per day	48	24	2.4	88	44	4.4	192	96	9.6
Time Between Possible Stop-Starts	0.02	0.04	0.22	0.02	0.04	0.22	0.02	0.04	0.17
Cycle Maximizes fuel Economy	0.99	0.5	0.05	0.99	0.65	0.05	0.99	0.85	0.07

7 - EXPERIMENTAL RESULTS AND ANALYSIS

Validation of this model is difficult. I primarily used discussions with automotive professionals at trade shows and compared the results to those featured in the literature review. This process led to a greater understanding of the challenges facing existing systems, as well as what challenges will affect future systems. The status quo in the industry is not acceptable, especially for customers in the U.S. It is well known in the industry that existing systems are failing at a much greater rate than anticipated. The literature's estimates for survival times, actual achieved benefits, and cost are all in line with what this model predicts. While specific numbers from actual suppliers cannot be quoted and are not considered official, in their research Burke and Eckhard note the weaknesses of current and planned technologies and where the long term strengths are.

The first important point to evaluate was the effect on the bill of materials cost of the vehicle. The current solutions offered on the market are single and dual batteries of both SLI and AGM varieties. Companies who are currently producing start/stop systems can only justify single battery systems in the North American market, regardless of the effect on warranty. In micro/mini-cars in Europe and in Asia, OEMs use single battery systems, which often lead to dimmed lights and other system failure issues. These issues are unacceptable to consumers.

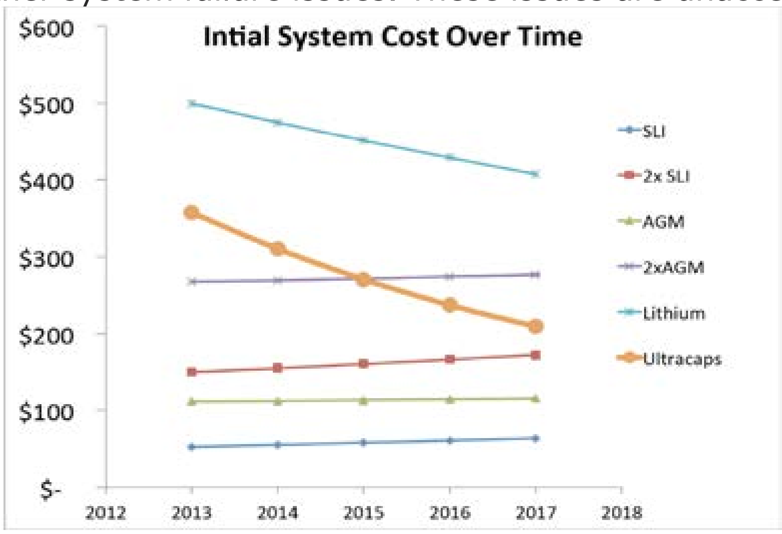

Figure 7.1: Initial System Cost

Lead acid batteries of both the SLI and AGM varieties are essentially commodities as their prices are sensitive to the cost of oil and lead. The cost of these products will increase in line with economic inflation and as a result of tighter governmental regulations.

While the cost of ultracapacitors and lithium ion batteries is decreasing, the reason for lithium's current low price is the result of competition and subsidies, neither of which is expected to hold out forever. The cost of ultracapacitors, however, has steadily decreased, primarily because of increased levels of automation in both the cell manufacturing and in the module manufacturing processes. The volume of EDLCs is growing at near 50% CAGR and the raw material production has also vastly improved. In Figure 7.1, the predicted cost of the ultracapacitor- based system is less than the cost of the current best solution - double AGM batteries - and is only about 20% more expensive than the dual SLI solution. The single battery solutions are too unreliable for this application and thus cannot be carried into North American MHV solutions. The next major consideration is the total system cost to the OEM.

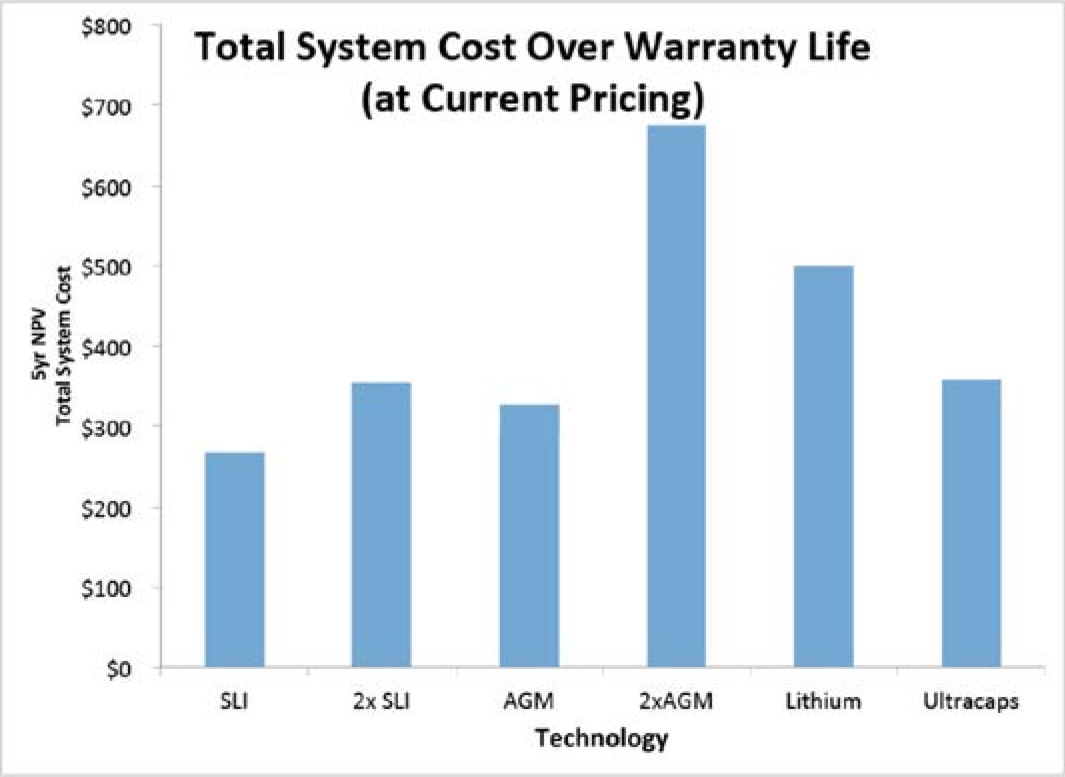

Figure 7.2: Total System Cost

Total system cost Figure 7.2, as noted before, includes the anticipated warranty cost for each of the technologies over each scenario. The analysis is also done at today's cost, further enhancing the conservative nature of this estimate. This estimate is done using the unlimited control algorithm, which generates identical economy for each of these scenarios. The ultracapacitors are only 15% more costly over three years at today's pricing as the least expensive solution. Further analysis shows that ultracapacitors over a 5-year period would be the lowest cost solution. The ultracapacitors likely would last the life of the vehicle, while the next longest solution is a lithium battery, which lasts, at most, seven years. These results are very strong for ultracapacitor-based systems, as anticipated cost reductions will be achieved and their reliability validated.

8 - FUTURE WORK

In order to move forward with an ultracap based product in the automotive sector, packaging and controls need to be developed that allow for simple drop in replacement of existing battery footprints and functionality. In addition, that packaging must be tested together with the capacitors in a mechanical shock and vibe endurance test that includes extremes in operating temperatures. Those cycles need to be defined by the OEMs and validated in 3rd party testing. Advance modeling (FEA) to ensure the survival of the product is vital because the design and test cycle is so long manufacturers cannot afford to be wrong.

Additionally, cost reduction efforts must be made on all of the key components of the capacitors; activated carbon, separator, can, terminal and balancing. The control systems and testing on the car to minimize the power and battery energy requirements will help insure the final product meets cost targets. In addition, efforts from the OEMs the minimize parasitic loses and or add energy scavenging technologies to maintain the battery in optimal condition while the vehicle is off will also help reduce total system cost.

In parallel, motorcycles over the years have developed technologies to reduce the power required to start their engines. This reduces battery size and starter size, thus reducing the overall weight of the motorcycle. These technologies could also be added to cars to make starting easier, further reducing the total cost of the ESS.

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