Cost Performance Estimating Relationships for Hybrid Electric Vehicle Components

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List of Acronyms

AC	Alternating Current
AGM	Absorbed Glass Mat
AHED	Advanced Hybrid Electric Demonstrator
AMS	Amsterdam Depot
ANL	Argonne National Laboratory
BTAP	Battery Technology Advisory Panel
C4I	Command, Control, Communications, Computers, & Intelligence
CARB	California Air Resources Board
COMBATT	Commercially Based Tactical Truck
CPER	Cost Performance Estimating Relationships
DARPA	Defense Advanced Research Project Agency
DC	Direct Current
EMA	Electro-magnetic Armor
EV	Electric Vehicle
FCS	Future Combat System
FTE	Full Time Equivalent
FMTV	Family of Medium Tactical Vehicles
GM	General Motors
GMO	GM Ovonic
HE	Hybrid Electric
HEMTT	Heavy Expanded Mobility Tactical Truck
HEV	Hybrid Electric Vehicle
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HV	High Voltage
ICE	Internal Combustion Engine
IGBT	Insulated Gate Bipolar Transistor
IITRI	Illinois Institute of Technology Research Institute
ITS	Institute for Transportation Studies
JSB	Japan Storage Battery Co.
LAV	Light Armored Vehicle
LMI	Logistics Management Institute
LRIP	Low Rate Initial Production
MTV	Medium Tactical Vehicle
MV	Manhattanville Depot
NAC	National Automotive Center
NBC	Nuclear, Biological, Chemical
NiMH	Nickel Metal Hydride
NYCTA	New York City Transit Authority
O&S	Operation and Sustainment
OEM	Original Equipment Manufacturer
OTC	Oshkosh Truck Corporation
PEM	Proton Exchange Membrane
PEVE	Panasonic Electronic Vehicle Energy
PFN	Pulse Forming Network
PM	Program Manager

RTS	Rapid Transit System
SAIC	Science Applications International Corporation
S&S	Stewart & Stevenson
TACOM	Tank-automotive and Armaments Command
TARDEC	Tank Automotive Research, Development, and Engineering Center
TTD	Transformation Technology Demonstrator
UDLP	United Defense Limited Partnership
UPS	Uninterruptible Power Supply
UT-CEM	University of Texas Center for Electro Mechanics
VRLA	Value Regulated Lead Acid

Executive Summary

This report documents hybrid electric vehicle (HEV) component cost performance estimating relationships (CPER) developed by Science Applications International Corporation (SAIC) for the Office of the Deputy Assistant Secretary of the Army for Cost and Economics under contract DASW01-97-D-0061 (Delivery Order 6). These CPER are tools that support cost estimation of HEV components. While this technology is still developing, recent advances make it likely that future military vehicles will contain HE systems. This technology is a significant departure from the power package and drive train technology seen on current generation vehicles. Estimation methods based upon these older technologies would miss important insight into the current state of technology.

These estimating tools develop methodologies for energy storage components, drive system components, and a supplemental armor solution. Using these, cost estimates for different combinations of components can be generated. This provides the basis for cost comparisons among those alternative configurations. It does not include the traditional vehicle components such as the frame, weaponry, C4I, wheels or tracks, crew stations, NBC, or special equipment. Separate estimates of these other vehicle systems would be combined with the hybrid electric system estimate to arrive at a vehicle cost estimate.

The report is divided into three sections. Section I, which encompasses chapter 1, provides the organization of the report and outlines the general methodology used to collect the data and develop the estimates contained in this report. Section II, encompassing chapters 2 through 5, describes the primary designs for hybrid electric power designs and provides estimates for the individual components of a hybrid electric vehicle system. Section III, which includes chapters 6 and 7, provides additional considerations for the cost estimation and modeling of hybrid electric vehicles.

Chapter two is an introduction to hybrid electric systems for military vehicles. It provides an overview of possible power train configurations. The two primary designs are series and parallel. Also included here is an introductory discussion of hybrid electric components and some current system integration efforts.

Chapter three deals with energy storage components: batteries, capacitors, flywheels, and fuel cells. For batteries, the types that are analyzed are Valve Regulated Lead Acids (VRLAs), Nickel-Metal Hydride, and Lithium Ion. VRLAs are the cheapest, while Lithium Ions are the most expensive. However, there are advantages in terms of weight, energy, power, and lifetime that make Nickel Metal Hydrides and Lithium Ions more appealing choices for hybrid electric vehicles. Capacitors offer an alternative to batteries for energy storage. However, they are more likely to be used in pulse power situations such as engine starting, quick acceleration boosts, and electro-magnetic armor. Batteries are more efficient for use in situations where sustained energy usage is required. Flywheels and fuel cells are discussed, but both of these technologies are too early in development to estimate accurately.

Chapter four looks at power train components: motors/generators, inverters/controllers, transmissions, engines, and off-board power generation. Two basic types of motors/generators are being used in hybrid electric applications: permanent magnet and AC induction. Permanent magnet motors are more likely to be used as generators, while AC induction motors are more efficiently used as motors. Inverters/controllers can be paired with each motor type, in addition to the other components in a hybrid electric vehicle. Electric transmissions are very early in development, so very little information is available. The same is true of high power density engines. Both of these are discussed. Off-board power generation is an application that is likely to be very important to the military. Hybrid electric vehicles can advance the cause of a more highly mobile force by providing power to other vehicles and systems on the battlefield.

Chapter five references electro-magnetic armor (EMA). This is a supplemental armor solution that is not an integral part of a hybrid electric system. However, the infrastructure provided by a hybrid electric power train can support EMA. The cost estimate for EMA is available to government agencies through the point of contact identified in Chapter 5.

Chapter six offers a brief analysis of operation and sustainment costs. We look at estimates of O&S costs for the military, as well as estimates of costs of commercial hybrid electric vehicles. In addition, it analyzes a study of actual O&S costs from New York City transit buses.

Chapter seven offers a discussion of the status of HEV development. This technology is in an evolutionary period, so the estimates developed here should be viewed as evolutionary as well. It will be important to ensure that they remain up to date, so that they are accurate tools into the future.

Section I – Background and Study Methodology

Chapter 1 – Background and Study Methodology

Background

The internal combustion engine (ICE) has been the primary source of automotive transport power for over a century. However, in response to growing concerns about fuel economy, environmental quality, and dependence on foreign sources of oil the government, automobile manufacturers, and automotive consumers are seeking out alternative methods of automotive power. One such alternative is hybrid electric vehicles. A hybrid electric vehicle combines two sources of motive power. The most common type is gas-electric hybrids, which combine an internal combustion engine with battery powered electric motors. These vehicles are being produced in commercial markets and are being developed for military applications. Other types of hybrids combine an ICE with a capacitor module, flywheels, or fuel cells. Battery powered hybrids, however, are the most advanced. Hybrid vehicles are being used to pave the way toward fuel cell vehicles, which will not be ready for widespread commercialization for another ten to fifteen years.

Hybrid electric automotive technology has made substantial progress in commercial markets in recent years. Toyota and Honda are producing hybrid electric passenger vehicles, with Ford and others preparing to enter the market. Transit agencies across the US are exploring hybrid electric technology as a solution to high fuel costs and pollution. The most high profile example is in New York City where the New York City Transit Authority (NYCTA) is purchasing 325 hybrid electric transit buses. For the Army, hybrid electric technology can provide silent watch, silent mobility, and a reduced logistics footprint. Current military hybridization projects include the Family of Medium Tactical Vehicles (FMTV), the High Mobility Multipurpose Wheeled Vehicle (HMMWV), the Heavy Expanded Mobility Tactical Truck (HEMTT), and the M113. Future vehicles such as Future Combat System (FCS) and the Commercially Based Tactical Truck (COMBATT) are likely to use hybrid electric technology.

Significant obstacles must be overcome before the technology becomes widespread. Many of the components that either do or will make up hybrid electric power trains are in their technological infancy. In particular, batteries capable of powering hybrid electric vehicles are still in development. Without further advances in this area, it is not likely that hybrid electric vehicles will gain significant market share either in commercial or military markets. Battery packs necessary to power these vehicles are large and heavy. The weight reductions due to engine downsizing often do not come close to the weight increases caused by the battery packs. Additionally, the space claim of the batteries is significant. While batteries and energy storage in general is the most significant obstacle, other components present challenges as well. The motors for hybrid electric vehicles are still developing and are being produced at low quantities. Further, high power density engines that could alleviate many of the weight and volume concerns are still in development.

Several additional obstacles exist in the context of military hybrid electric vehicles. Consumer acceptance of hybrid electric vehicles in commercial markets will drive the feasibility of widespread hybridization in both commercial and military markets. Many future cost projections assume full market penetration of hybrid electric vehicles and components. If this does not happen, hybrid electric vehicles may be prohibitively expensive. In this case, they may become a vehicle that serves a few narrow purposes.

Additionally, it is not clear that engine downsizing is viable in a military context. Military vehicles may require the option of operating at full power at all times. For example, a vehicle that has done a significant silent watch, and has drained the battery must still be able to operate at full power should it be necessary to leave the silent watch area quickly. This will likely require an engine size equal to that of a conventional version of the same vehicle. Thus, the development of high power density engines is critical to the development of military hybrid electric vehicles.

Data Collection & Database Development

The data collection and database development process consisted of three steps. First, experts in government and industry were contacted with regard to the components and systems being studied. Initial and follow-on interviews were conducted on vehicle power trains, and energy storage. These interviews provided an overview of the current state of hybrid electric vehicle technology and provided rough costs. Further, they provided additional contacts within industry and government. Figure 1 provides a list of the organizations contacted in the course of this study.

National Automotive Center	ISE Research Corporation
PM HE HMMWV, FMTV, Stryker	S&S
UDLP	OTC
SAFT Batteries	DARPA
TARDEC Propulsion, Power	Maxwell Capacitors
Army Electro-magnetic Armor Development	Kold Ban Capacitors
Army Combat Hybrid Power System	Marathon Generators
U of TX Center for Electro Mechanics	UQM Motors
Southwest Research Institute	IITRI
Allison Transmissions	Argonne National Laboratories

Figure 1: Points of Contact List

The second step was to use the knowledge gained from step one to locate available open source information. The primary source of this information was manufacturer websites. This data was collected and catalogued for CPER development. In some cases publicly available information provided enough data to begin developing CPER. This was the case with lead acid battery technology. In other cases the public information provided initial leads, but did not allow for CPER development, as was the case with capacitors.

The third step was to collect the additional information necessary to develop CPER. This was accomplished by contacting representatives of hardware manufacturers, equipment suppliers, and research institutions to obtain information on component costs, and to clarify confusing or conflicting technical information.

Cost Performance Estimating Relationship Development

Hybrid electric vehicle system components are in various stages of development. As a result the data available for analysis varies widely. For components where ample data exist, the approach to CPER development was to collect data from multiple sources, identify significant independent variables and fit a cost equation to the data.

In many cases, the components are either not mature or not tailored to HEV applications. In this situation, the approach was to interview subject matter experts. We obtained the limited data that exists as well as insight into trends, technical barriers, and manufacturing that allowed us to develop basic relationships and factors for development, prototype, low rate production, and production phases.

Section II – Hybrid Electric Power Trains and Components

Chapter 2 – Hybrid Electric Power Trains

Hybrid electric (HE) power trains fall generally into one of two designs: parallel or series. Each uses an internal combustion engine to generate power. A parallel design maintains the mechanical link between the engine and the drive wheels. A series design converts all the energy to electricity, which is sent to the drive wheels. There are variations on these designs, as some hybrid systems combine the two main configurations. However, since all designs are based on one or both of these, the discussion will focus on them.

Series Design

A series HE system has no mechanical connection between the engine and the wheels. All the energy from the engine drives a generator and is converted to alternating current (AC) electricity. It is then converted to direct current (DC) electricity and stored in batteries or capacitors. When the power is required, it is converted back to AC electricity and used to power the drive motors. This is illustrated in Figure 2.

There are several possible configurations for a series hybrid system. In one configuration the drive motors are located in front of the existing differential gearboxes in the front and rear axles. Another design places the drive motors at each wheel station, eliminating the differential gears and drive shafts. Examples of systems that currently use the series configuration are the Hybrid Electric HMMWV and the Oshkosh HEMTT Propulse.

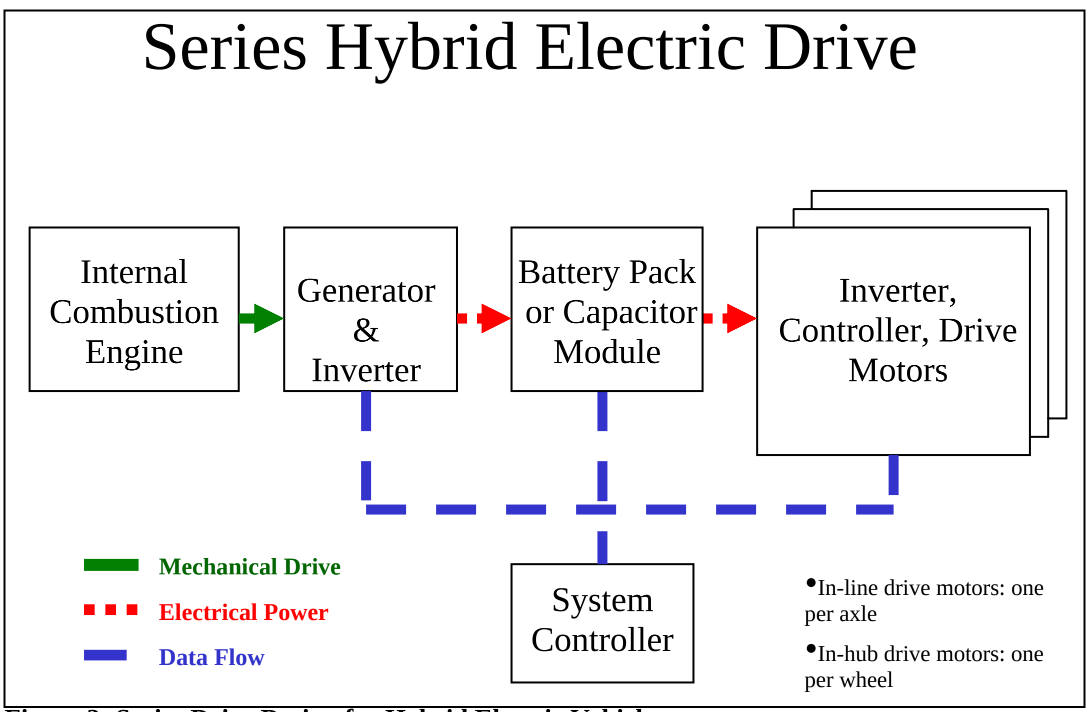

Figure 2: Series Drive Design for Hybrid Electric Vehicles

Parallel Design

In a parallel HE system the engine is coupled mechanically to the wheels. It also has generator/motors that can draw power off of the drive train and store it electronically in batteries or capacitors. This stored power can be fed back through the same generator/motor into the transmission to add torque to the drive train. Thus the engine can create a store of energy when the duty load is light and can be supplemented by that stored energy when the duty cycle is heavy. The stored energy can be made available for non-mobility or off-vehicle purposes. This configuration is depicted in Figure 3. It is being used for several ongoing hybrid electric systems, including the developmental hybrid electric Medium Tactical Vehicle (MTV) being developed by Stewart and Stevenson and the New York City Transit buses. These programs use a parallel design electric transmission manufactured by Allison.

Hybrid hydraulic power trains are another variation of the parallel hybrid system. The mechanical link between the engine and the wheels still exists and it is augmented with stored energy. A hydraulic pump/motor is mounted on the drive shaft. In the charging mode, the pump runs off the drive shaft and builds pressure in an accumulator. In the discharging mode, the stored pressure drives the pump/motor, which imparts torque to the drive shaft, augmenting the engine. This configuration is not considered in this study analyzed because no active hybrid hydraulic programs have been identified.

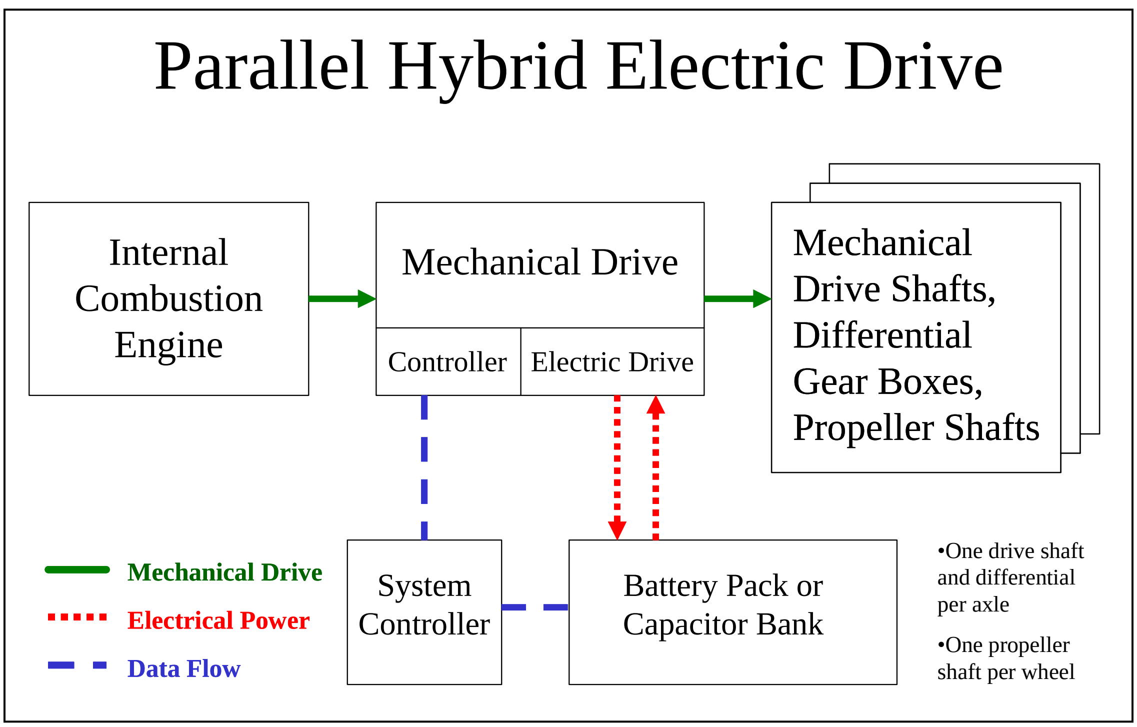

Figure 3: Parallel Drive Design for Hybrid Electric Vehicles

Hybrid Electric Components

The major hybrid electric component categories analyzed are energy storage and power train. Energy storage possibilities include batteries, capacitors, flywheels, and fuel cells. Power train components include motors, generators, controllers, inverters, transmissions, and engines.

In this report we discuss four program phases for most components: development, prototype, low rate production, and full production. There are varying degrees of data availability for each. Data is most abundant for low rate and full production costs for each of the components. Prototype costs are available to a lesser extent, but we are able to develop reasonable estimates for this phase for many components. Data is very limited for component development costs.

The costs to develop HEV components, subsystems and systems are very difficult to estimate due to a number of factors. First, the available documentation is limited, as much of the effort is privately funded. The areas of research, the status of the progress, the technology barriers and the strategic alliances are often closely guarded proprietary information. Second, the development efforts often are derived from other related programs and contribute to other programs, making it difficult to separate costs. The effect is that the costs to develop specific products are blurred by association with other developmental efforts. A third consideration is the uncertainty of the HEV configuration to host the components. The host vehicle environment is somewhat fluid. Areas that will influence development costs include the following: electromagnetic interference, ruggedization, shock and vibration, duty cycle and system configuration. These areas affect the design specifications that drive the development budgets.

Through interviews with the HE community, several development cases-in-point were discussed. Order of magnitude estimates were offered based on actual experience, vendor quotes and engineering estimates. These have been collected to provide the best information available for estimating the development costs of various HE components, subsystems, and systems.

Chapter 3 – Energy Storage Components

Energy storage is the most significant obstacle to widespread market integration hybrid electric vehicles, particularly in the military market. Military vehicles require significant energy storage for cooling the crew and electronic equipment, as well as for silent mobility and silent watch. The battery pack necessary to meet the energy storage and power needs of a hybrid electric vehicle makes significant weight and space claims on the vehicle. This is because gasoline has greater energy density and specific energy than batteries.[1] Thus, in order to provide the same level of energy storage as conventionally powered vehicles, hybrid electric vehicles must dedicate a larger proportion of vehicle weight and volume to energy storage. This produces a severe weight penalty as a result of large battery packs. In order to make hybrid electric vehicles viable military alternatives, these energy density and specific energy issues must be addressed.

Substantial investment has been made in technologies that provide improved energy density and specific energy, while also being safer and cleaner than existing technology. New battery technologies include Valve Regulated Lead Acids (VRLA), Nickel Metal Hydride (NiMH), and Lithium Ion. Other energy storage technologies being developed include ultra capacitors, flywheels, and fuel cells. CPERs are developed the battery technologies, as well as ultra capacitors. Flywheels and fuel cells are discussed, but are too early in development for reliable estimation.

Batteries

Batteries are likely to continue to meet near-term automotive energy storage needs, hybrid-electric or otherwise. However, the battery currently most common in automotive applications, the liquid lead acid battery, while relatively inexpensive, is inadequate in terms of energy density and specific energy. Also, if cracked or tipped over, it will spill acid, and it produces hydrogen when being charged. These situations cause hazardous conditions and make air transport with filled batteries impossible.

New battery technologies promise to satisfy the energy storage and power requirements for hybrid electric vehicles while reducing weight and volume. They are in various stages of development, and cost more than current technology. These include advanced lead acid batteries and entirely new battery technologies. The advanced lead acids, known as Valve Regulated Lead Acids (VRLAs), avoid the spillage and leakage problems of conventional liquid lead acid, while also providing superior performance. The new technologies, which include Nickel Metal Hydride (NiMH), Lithium Ion, Lithium Polymer, and Nickel Cadmium, provide energy density, specific energy, power, lifetime, and storage life advantages over all forms of lead acid batteries, new and old. They have higher initial costs than the VRLAs, due partly to an earlier stage of development, and partly to higher material costs. The latter means they are likely to

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[1] Cuenca, R.M., L.L. Gaines, & A.D. Vyas, "Evaluation of Electric Vehicle Production and Operating Costs," Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, November 1999.

remain more expensive when compared to full production VRLAs. However, their longer life and other benefits associated with weight and volume gains will mitigate the higher cost over the course of a vehicle's life.

General Methodology

CPER are developed for NiMH, Lithium Ion, and VRLA batteries. Each battery type is estimated as a function of energy storage, with kilowatt-hours being the standard metric. The two other battery types mentioned are discussed but are not estimated. Lithium Metal Polymer batteries are too early in development to estimate. Nickel Cadmium batteries are not likely to be used for reasons that are discussed.

The requirements of HEV are severe enough that individual batteries must be packaged together to achieve the necessary power and energy. These packs require systems to manage the electrical and thermal performance of the individual batteries. Lithium Ion and NiMH batteries are typically chosen for HEV applications, and are thus normally packaged for that purpose. The available data for these two battery types includes the cost of this packaging, and the CPERs that were developed estimate the full cost of the battery packs: the batteries, controls and container. Since VRLA batteries are primarily used in commercial automotive applications, the data on them represents the costs of individual batteries. A separate factor to account for the cost of assembling the VRLA into a pack had to be developed.

A general limitation of these CPERs is that they represent commercial market batteries. Insufficient data exists to estimate the cost of militarization.

Valve-Regulated Lead Acid Batteries

Two types of VRLA batteries have been developed: Absorbed Glass Mat (AGM) and Gel. AGM batteries hold the electrolyte in a glass mat between the plates, while Gel batteries use a thick gel. Both have the advantage over liquid lead-acid batteries in that they do not spill or leak. This satisfies the safety requirements for air transport. Both provide more power and energy and deep cycle better than liquid lead-acids. Both require less maintenance than a flooded battery and have better shelf lives. The normal shelf life of a charged liquid lead-acid battery is six months, while an AGM's is a year and a Gel's has been demonstrated to be two years. Liquid lead-acid batteries are stocked by the Army in both a wet and a dry configuration, with acid stocked separately. No dry versions of AGM or Gel batteries would need to be stocked by the Army, which will reduce inventory costs.

These batteries are likely to remain more expensive than liquid lead acid batteries because they require lead with higher purity. AGMs have been commercially available for more than three years and Gels have been in production for ten, so price is not expected to fall significantly with increased production quantities. Further, military consumption of lead acid batteries represents about 1% of the market, so significant purchases by the military are not likely to have a large effect on price.

While these batteries represent an improvement over older lead acid technology, they do not offer the potential energy density, specific energy, power, and lifetime benefits of Lithium Ion or Nickel Metal Hydride batteries. Hybrid electric systems that use these batteries include the prototype buses purchased by NYCTA, which use Hawker Sealed Lead Acid batteries and the HE HMMWV.

Data

The data for these CPER comes from a battery retailer website.[2] These are production quantity batteries, so these are estimates of production only. Again, note that these CPER are limited by the fact that these are commercial grade batteries. Insufficient data exists to estimate the cost of militarization.

Methodology

VRLA battery packs are estimated in two steps. The first step estimates the cost of the batteries. The second step estimates the cost of integrating the batteries into a pack.

Estimate: AGM Batteries

The CPER developed for AGM batteries indicates that energy storage capacity has a positive and significant effect on battery cost. The CPER statistics are displayed in Figure 4, and a graph of the data is shown in Figure 5.

CPER Equation				
Cost = 56.681 + 112.14 * kWh				
Definitions				
Cost	Retail cost of the battery (in 2003 $)			
kWh	Kilowatt-hours			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	56.68	5.66	10.01	
kWh	112.14	5.03	22.31	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
85.83	28.96	83	81	+33.29, -31.54

Figure 4: AGM Battery CPER Statistics

[2] www.americanbatteries.com

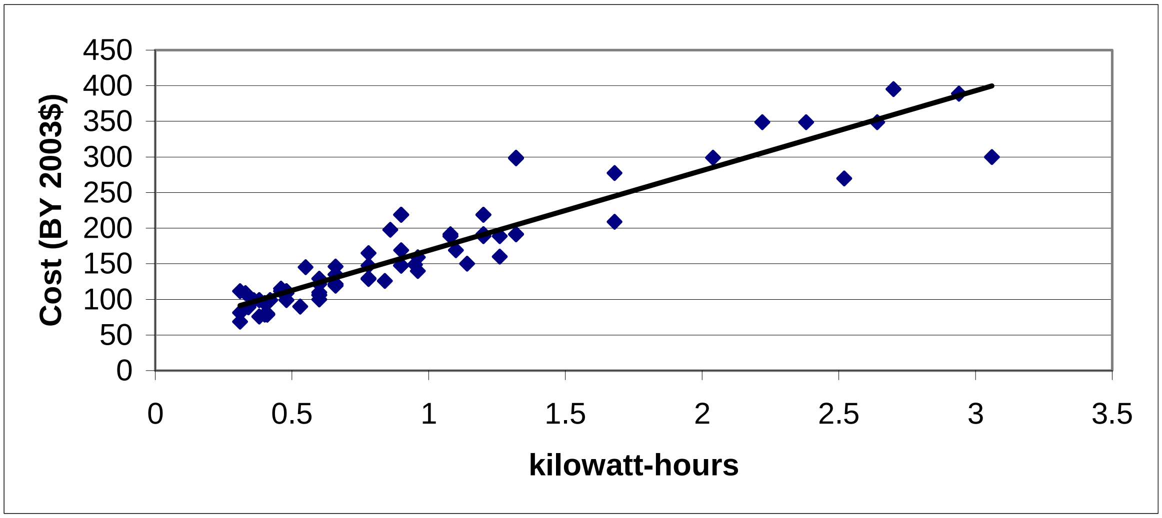

Figure 5: AGM Battery Costs v. Kilowatt-hour Plot

This equation estimates the cost of single batteries. The results of this equation must be multiplied by the number of batteries in order to obtain the total battery cost of an integrated battery pack.

Estimate: Gel Batteries

The Gel CPER indicates that energy storage capacity has a positive and significant effect on battery cost. The CPER statistics are displayed in Figure 6 and a graph of the data is shown in Figure 7. As with the AGM batteries, this equation estimates the cost of single batteries. The results of this equation must be multiplied by the number of batteries in order to obtain the total battery cost of an integrated battery pack.

CPER Equation				
Cost = 36.268 + 186.90 * kWh				
Definitions				
Cost	Retail cost of the battery (in 2003 $)			
kWh	kilowatt-hours			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	36.27	21.48	1.69	
kWh	186.9	15.43	12.12	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
90.11	43.57	17	15	+22.74, -19.72

Figure 6: Gel Battery CPER Statistics

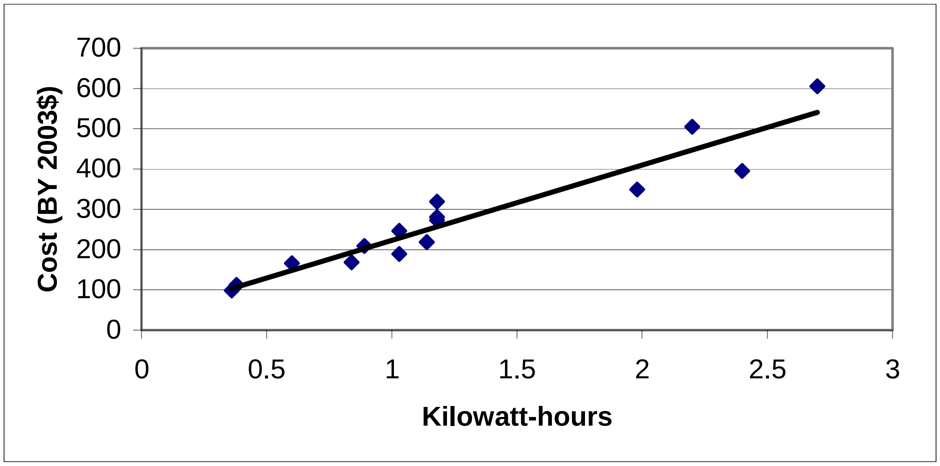

Figure 7: Gel Battery CPER Cost v. Kilowatt-hours Plot

Battery Pack Costs

Most HEV systems use NiMH or Lithium Ion batteries, so there are few cases where the cost of creating a VRLA battery pack is documented. In one laboratory configuration to support a pulse power study, 50 twelve volt batteries were packaged to produce a 600V system. The batteries cost $2,000 and the packaging switches, cabling, and container cost $4,000. In another application, a tactical wheeled vehicle uses 24 twelve volt batteries to comprise a nominal 300V system which were purchased for $8,000. Here the packaging also cost $4,000. In the first case, the packaging was strictly a laboratory brassboard for the electrical control of parallel- and series-connected batteries. In the second case, the pack was a prototype configuration that included thermal management as well as electrical control. Because the purpose of the battery pack influences the degree of electrical and thermal control required, there is much variability in the cost of the pack hardware with respect to the cost of the batteries.

Discussions with battery pack integrators suggest the following VRLA battery pack integration cost factors. These factors represent the cost to be added to the batteries to package them, manage their electrical performance, and interface with the vehicle power and data busses. The prototype factors are higher than the production factors because the amount of engineering and hand work is much higher than is required during production. The range of the factors takes into account the relative complexity of the application of the battery pack - the more demanding the work environment, the more sophisticated and expensive the battery pack. A simple application may include brief infrequent discharges, such as vehicle starting. A more complex duty cycle would have lengthy variable discharges, such as C4I equipment or drive motors. The depth of discharge is a factor. Deep discharge requires more control than light discharge. Whether the batteries are recharged as they are used or recharged after the mission will affect the cost. Tasks involving silent mobility or high voltage will require more expensive packaging than tasks with the engine running or low voltage. The estimator should consider the relative complexity of the intended duty cycle in selecting which part of each factor range to apply to the estimate.

Prototype Battery packs: Add 100% to 200% to the cost of the batteries.
Production Battery Packs: Add 25% to 100% to the cost of the batteries.

Nickel Metal Hydride Batteries

Nickel Metal Hydride batteries have developed as an alternative to lead acid batteries for automotive applications. They are used extensively in consumer electronics and are more developed for automotive applications than Lithium Ion batteries. They are currently used on the Toyota Prius, the Honda Civic Hybrid, and will be used on the hybrid Ford Escape. Compared to liquid lead acid batteries NiMH offers the same performance for half the weight and also offer increased battery life.[3] The most significant challenge to further development is that NiMH battery packs require significant thermal monitoring and active management of the battery temperature. They operate in a narrow temperature range, so the ability to heat or cool the battery pack is necessary. Additionally, the energy flow must be controlled for each individual battery. While they are more developed than Lithium Ion batteries, the technology is still developing, and cost is a significant barrier to full market penetration. The major manufacturers of NiMH batteries are GM Ovonic (GMO), Panasonic EV Energy (PEVE), and SAFT. NiMH batteries are being considered for the Army's Future Combat System (FCS)

Data

The data comes from two sources: a study done for The Energy Foundation[4] and a study done for the California Air Resources Board (CARB)[5]. Both sources estimate the cost of notional NiMH batteries across a range of battery capacities. The data used is based on batteries available in the 2010 timeframe. Recent price quotes for NiMH batteries are in line with the results of the equations here. Also, given that military hybrid electric vehicles are not likely to begin reaching production quantities for several more years, the equation developed here is a valid estimator of NiMH batteries. Like the VRLAs, this data represents commercial grade batteries. Insufficient data exists to estimate the cost of militarization.

Methodology

The approach to estimating NiMH batteries involves combining The Energy Foundation and CARB studies. The CARB study contains data on battery packs with cells rated at 10 to 150 Amp hours,[6] covering batteries likely to be used in commercial hybrid electric vehicles and batteries likely to be used in military hybrid electric vehicles. Additionally, it provides costs for two different battery production quantities, 20,000 per year and 100,000 per year. However, the data in this study represents costs to the original

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[3] Toyota is currently offering an 8 year, 100,000 mile warranty on the Prius battery pack
[4] Delucchi, Mark A. and Timothy E. Lipman, *Hybrid-Electric Vehicle Design Retail and Lifecycle Cost Analysis,* Analysis and Report Prepared for The Energy Foundation, April 2003.
[5] Lipman, Timothy E., *The Cost of Manufacturing Electric Vehicle Batteries*, Report for the California Air Resources Board, May 1999.
[6] Kilowatt hours are derived by multiplying a battery's amp hour rating by its Voltage. Thus: kWh = V * Ah

equipment manufacturer (OEM) and omits the costs to integrate the battery into a vehicle and the mark-up from the cost to the OEM to the retail price to final consumer.

The Energy Foundation study provides data that reflects the final cost to consumers. However, the batteries are low kilowatt-hour systems suitable only for commercial hybrid electric vehicles. The systems range from 0.76 kWh to 4.91 kWh. Military hybrid electric vehicles will require energy storage capacities that are 5 to 10 times greater than the upper range of this. The CARB study indicates that the cost per kilowatt-hour decreases as kilowatt-hours increase. Thus, an equation based upon the Energy Foundation data will overstate the cost of NiMH batteries for the larger systems required for military vehicles.

Equations are developed from the data contained in both studies. These equations are then combined to produce a final result that takes into account a large range of battery sizes and quantities. The Energy Foundation study data is used to develop an equation that is valid for batteries with capacities of 0 to 5 kWh and are produced in quantities of 100,000 packs per year. The CARB study data is used to develop an equation that estimates the percentage change in cost per kilowatt hour as a result of changes in quantity and battery energy storage capacity. The combination of these produces an equation that estimates the cost of a wide range of NiMH batteries in quantities of 20,000 per year or greater.

Base Equation

The base estimating equation developed from the CARB study data indicates that kilowatt-hours have a positive and significant effect on battery cost. The results are shown in Figures 8 and 9. This is a valid estimating equation for batteries with energy storage capacities between 0 and 5 kWh that are produced in quantities of 100,000 packs per year.

CPER Equation				
Cost = 187.76 + 1233.64 * kWh				
Definitions				
Cost	Retail cost of the battery (in 2000 $)			
kWh	kilowatt-hours			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	187.76	81.99	2.29	
kWh	1233.64	37.37	33.01	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
97.84	204.94	25	23	+18.41, -10.74

Figure 8: Nickel Metal Hydride Battery Base CPER Statistics

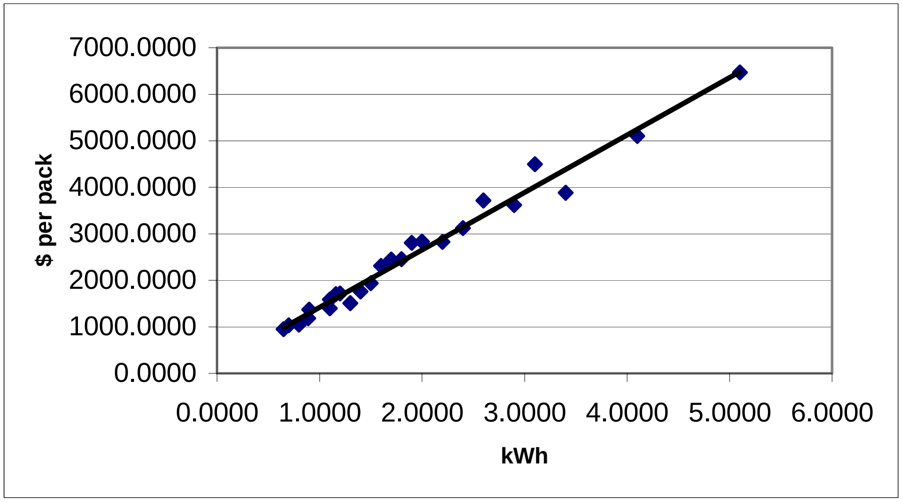

Figure 9: Nickel Metal Hydride Battery Cost v. Kilowatt-hours Plot

Quantity and Size Adjustment

Military vehicles are likely to have energy storage requirements significantly greater than 5 kilowatt-hours. Additionally, NiMH production is not currently at the full production levels of 100,000 packs per year. Thus, an equation is developed to account for size differences and quantity variations. The equation estimates the natural log of cost per kilowatt hour based on kilowatt hours and quantity. The result is an equation that estimates the percentage change in cost per kilowatt hour as a result of changes in kilowatt-hours and quantity. The results indicate that increasing battery size and quantity have significant negative effects on cost per kilowatt hour. This is shown in Figure 10.

CPER Equation				
$/kWh = 312.6 * EXP(-2.2742e^{-6}*Q) * EXP(-0.01179*kWhp)				
Definitions				
$/kWh	Battery pack cost per kWh			
kWhp	kilowatt-hours of the battery pack			
Q	Quantity of battery packs produced per year			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	5.7448	0.043	133.6539	
kWhp	-0.0118	0.0012	-10.2511	
Q	0.0000	0.0000	-5.2635	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
94.92	0.0489	8	5	+4.1312, -6.0147

Figure 10: Nickel Metal Hydride Battery Size/Quantity Adjustment CPER Statistics

Final Equation

The final equation is created by plugging the base equation into the quantity/size equation in place of the constant. In order to combine these two equations, the assumption is made that integration costs and the final mark-up are a fixed proportion of the base cost to the OEM. The quantity/size equation is based on data that reflects the cost of the batteries to the OEM. Thus, integration and final mark-up are excluded. In addition to this assumption, three adjustments must be made in order to ensure that this equation estimates correctly. First, the base equation must be divided by kilowatt hours, so that it is stated in terms of cost per kilowatt hours as the quantity/size equation is. Second, the base equation is valid for quantities of 100,000 packs per year. Thus, the final equation should reflect no quantity adjustment when the production quantity is at this level. Therefore, the Q in the quantity size equation must be changed to Q*, where Q* = Q - 100,000. Thus, when Q = 100,000, Q* = 0. Since this variable is expressed as an exponent and is multiplied by the constant, the result will be no change in the price at the quantity of 100,000 packs per year. Finally, the third adjustment is to multiply the entire combined equation by kilowatt hours to get a cost for the entire pack, as opposed to a cost per kilowatt hour. These steps are illustrated below.

The base equation is:

Cost = 187.8 + 1234 * kWh

This equation is useful for estimating the full cost of NiMH battery packs with storage capacities between 0 and 5 kWh at production levels of 100,000 packs per year.

The quantity/size equation is:

$$\$/kWh = 312.6 * e^{-2.2742e-6*Q} * e^{-0.01179*kWh}$$

This equation is useful for estimating the manufacturing cost of a wide range of NiMH batteries in quantities of between 20,000 and 100,000 packs per year.

Combining these two equations as described above yields:

$$Pack\ \$ = (((187.8 + 1234 * kWh)/kWh) * e^{-2.2742e-6*Q*} * e^{-0.01179*kWh}) * kWh$$

The base estimating equation replaces the quantity/size equation constant because it reflects the total cost to consumers of NiMH batteries. The multiplicative terms adjust the price of the battery based upon battery size and battery quantity. The combined equation is useful for estimating the full cost of producing between 20,000 and 100,000 packs per year of a wide range of NiMH batteries.

Development, Prototype, and Low Rate Production Costs

There is little data available for development costs of Nickel Metal Hydride batteries. The only data point for development is a TARDEC development project for a NiMH to be used in military vehicles. This is a $5 million development effort.

There are several studies that shed light on low rate production costs. A study by the Battery Technology Advisory Panel estimated the cost of low production NiMH batteries at $2000 per kWh.[7] This study estimated full production costs at about $250/kWh, which now appears to be an unrealistically low estimate based on available information. However, the ratio of low rate production to full production costs of 4 to 1 is a useful data point. This ratio is confirmed by other data contained in the CARB study used to develop the quantity/size equation for production.

The CARB study provides estimates for four generations of NiMH batteries at quantities of 350; 7,700; 20,000; and 100,000 packs per year. The data is displayed in Figure 11.

Technology	350 packs/yr	7,700 packs/yr	20,000 packs/yr	100,000 packs/yr
Generation 1	$1,079/kWh	$413.5/kWh	Not examined	Not examined
Generation 2	Not examined	$341/kWh	$270.5/kWh	$234.5/kWh
Generation 3	Not examined	Not examined	$259/kWh	$224.5/kWh
Generation 4	Not examined	Not examined	$198.5/kWh	$165.5/kWh

Figure 11: CARB Study NiMH Costs

This chart can be filled in using ratios of the production level costs contained in the chart. For example, the cost per kWh of Generation 1 batteries at 20,000 packs per year can be estimated by using the ratio of the cost of Generation 2 batteries at 20,000 packs per year to the cost at 7,700 packs per year. Similar calculations are done for each cell to generate the costs in Figure 12.

Technology	350 packs/yr	7,700 packs/yr	20,000 packs/yr	100,000 packs/yr
Generation 1	$1079/kWh	$413.5/kWh	$328/kWh	$284.4/kWh
Generation 2	$889.8/kWh	$341/kWh	$270.5/kWh	$234.5/kWh
Generation 3	$852/kWh	$326.5/kWh	$259/kWh	$224.5/kWh
Generation 4	$653/kWh	$250.2/kWh	$198.5/kWh	$165.5/kWh

Figure 12: NiMH Cost Projections for Various Technology and Production Levels

Using this data, we can develop factors between different production levels. The most important in this case is the factor between 350 packs per and 100,000 packs per year, which represents a ratio between low rate and full production costs. This factor, for Generation 4 batteries, is 3.95. Again, we assume that integration and the final mark-up vary proportionally with the base costs to the OEM; otherwise, the estimates would

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[7] Anderman, Menahem, Fritz R. Kalhammer, and Donald MacArthur, *Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability*, The Year 2000 Battery Technology Advisory Panel, Prepared for the State of California Air Resources Board, June 2000.

become skewed as these costs are added. This factor is roughly the ratio of low rate production to full production found in the BTAP study.

There is no data available on NiMH battery prototype costs. The most reasonable available estimate for prototype batteries is the low rate production cost estimate developed here.

Lithium Ion

Lithium Ion batteries represent a performance improvement of roughly 66% in terms of power density over Nickel Metal Hydride batteries. However, they are at an earlier stage of development for automotive uses, although they are used extensively in consumer electronics. Compared to liquid lead acid batteries Lithium Ions are one-fourth the weight for the same performance, thus demonstrating improved energy density and specific energy. Lithium Ion batteries generate less heat during operation than NiMH batteries and therefore requires less temperature control. Less temperature control implies a less expensive battery pack, however the cost of the batteries themselves make the Lithium Ion battery packs the most expensive alternative for HE vehicle designers. Benefits of the Lithium Ion's superior power and energy density have to be traded against the higher acquisition costs. Current problems with Lithium Ion batteries for automotive purposes include cost, safety, and operating life. Industry currently lacks the production facilities to produce these batteries in large quantities. The three major manufacturers of these batteries are Japan Storage Battery Co. (JSB), Shin-Kobe, and SAFT. These batteries are currently in use on the Nissan Altra and are also being considered for the Army's FCS.

Data

Data for Lithium Ion automotive batteries is sparse. Most is anecdotal and an insufficient amount exists to develop robust CPERs. Data sources include the Battery Technology Advisory Panel study, Lithium Ion manufacturers, and hardware system integrators. A study by the Argonne National Laboratory (ANL)[8] provides the most robust data, building costs based on estimated material, labor, overhead, and administrative costs. However, these estimates are significantly lower than other sources. A possible explanation of this is that this study assumes full market penetration and high volume production, situations that do not currently exist, and are not likely to exist in the near future. While these costs are possible, they are not likely in the short run. Thus, they are not considered for this report.

Estimate

The estimate for Lithium Ion batteries is based upon anecdotal information. A data set sufficient to produce robust CPERs is not available. The estimates here are rough order of magnitude costs that were developed considering all of the available information.

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[8] Gaines, Linda and Roy Cuenca, *Costs of Lithium-Ion Batteries for Vehicles*, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, May 2000.

Both the prototype and the production costs are based primarily on discussions with industry experts and hardware systems integrators. Figure 13 characterizes the costs of Lithium Ion automotive batteries based on current information.

Phase	$/kilowatt-hour
Prototype	10,000
Production	3,300

Figure 13: Lithium Ion Battery Costs

The production costs estimated here assume significant government subsidization of production facilities. Industry claims that in order to be competitive with Japanese manufacturers of Lithium Ion batteries, such subsidization is necessary, as the Japanese government is subsidizing a production facility for Lithium Ion batteries[9].

Advanced Battery System Development and Integration

The data available for advanced battery (such as Lithium Ion or NiMH) system development and integration costs is sparse and anecdotal, as well. Insufficient information exists to develop robust CPERs. The few data points are listed here to serve as guidelines for these costs.

One estimate calls for $600K to develop and demonstrate a 600 Volt lithium ion battery pack. There is an estimate that it costs $1.5M to develop and integrate an operational prototype of a battery pack, independent of battery type. This represents engineering, development, assembly, test and evaluation up through the first build of the pack, including the inverter, mechanical pump, and controller. Costs not included are batteries, lab facilities and test equipment. This includes the cost of ensuring all the pieces work effectively together. Another estimate places non-recurring engineering development costs for a NiMH battery system for a combat vehicle platform between now and 2010 to be about $20M.

Other Battery Technologies

There are two other battery technologies worth mentioning that are not analyzed in this report: Lithium Polymer and Nickel Cadmium. They are not strong short to medium term candidates to be placed in military hybrid electric vehicles.

Lithium Polymer

Lithium Polymer batteries are even more developmental than Lithium Ions. These batteries have a higher theoretical specific energy than NiMH or Lithium Ion. However, the current actual specific energy and energy density is not better than the best Lithium Ion batteries. The advantages over Lithium Ion, should they achieve the energy goals are improved safety and lower cost. However, the manufacturing requirements are likely to be more stringent for these batteries, possibly offsetting cost advantages. These batteries

[9] Information gathered from a conversation with the HE HMMWV Program Office, April 16, 2003.

are not likely to be ready for full production and widespread use in vehicles for another 15 years.

Nickel Cadmium

Nickel Cadmium batteries are not likely to be used for electric or hybrid electric vehicles in the US. They are widely used in electric vehicles in Europe, particularly France. These batteries have excellent cycle life and can be expected to last the life of an EV in normal operation. However, there are several problems with Nickel Cadmiums that make them unlikely candidates for wide market penetration in the US. First, they have lower energy densities than NiMH and Lithium Ions. Second, their initial costs are projected to be higher than other advanced batteries. The supply of cadmium is limited, which could cause a rise in the price of the batteries should they be mass produced. Finally, cadmium is generally considered to be a toxic metal, so there are environmental and health concerns with these batteries.

Ultra Capacitors

Capacitors are a possible alternative to batteries as a power source for hybrid electric vehicles. The capacitors discussed in this section are ultra capacitors. They can be designed for increased power (a pulse capacitor) or for increased energy storage (a traction capacitor). Ultra capacitors have slower discharge times than conventional capacitors. Where very fast discharge times are required, conventional capacitors are used. An example of this is electro-magnetic armor, referenced in chapter 5. Ultra capacitors charge and discharge much more quickly than batteries. While a battery could be expected to discharge over hours, a capacitor would discharge in seconds. Capacitors have a far greater lifetime than batteries, and are expected to last the life of the vehicle. However, they store relatively little energy compared to batteries. They are well suited for high power needs such as starting the engine or delivering a burst of power over a relatively short interval. Even traction capacitors, designed for increased energy storage, cannot provide energy over durations associated with silent watch periods.

Individual capacitor cells do not provide enough power to accomplish vehicle mobility or other primary capabilities. The cells must be packaged into modules of cells to develop the energy and power levels required. The module also contains a controller for the electrical and thermal performance of the individual capacitor cells. Individual capacitor cells may be purchased from manufacturers and integrated into packs. Fully integrated modules, ready for installation into vehicles, are also available commercially.

The degree of control required in the module depends on the duty cycle that the capacitors must perform. TARDEC is currently developing an ultra capacitor module for engine starting in a conventional tactical vehicle, which is a light duty cycle. Passive controls are sufficient for light duty cycles. In hybrid electric vehicles, the duty cycle is more rigorous because the capacitors would also power the drive train components and ancillary vehicle loads. Active controls, using data sensors, processors, and response hardware, are required for heavy duty cycles. The cost of the control system would be significantly higher in the more rigorous hybrid duty cycle.

Because the use of capacitors in the automotive industry is in its infancy, there are no manufacturing facilities capable of producing large numbers of uniform-quality automotive-sized capacitors. Prototypes are hand made and performance qualities vary considerably. This requires careful balancing and energy management between cells regardless of the duty cycle. Limited numbers of ultra capacitors have been mass produced. Once in full scale production, the cost and quality of individual cells will improve significantly and the cost of the controls will decline.

Data

Cost data for ultra capacitors was collected during discussions with representatives of capacitor manufacturers and integrators, and was cross checked with experts at TACOM. Data for ultra capacitors used for automotive purposes is limited. However, rough costs were obtained that provide some insight as to cost trends for individual capacitors. This included the cost of single prototype, low-rate production, and full production capacitors. In addition, rough data for the cost of assembly into modules were provided.

Methodology

The industry standard for the cost of capacitor cells is as a function of capacitance, for which the unit of measure is farads (F). Cost-per-farad is a good measure of the cost of the cells that make up the modules used in the vehicles. Cost-per-farad trends, as a function of production quantity, are good indicators of the cost of capacitor products in prototype, LRIP and full production. Costs for capacitor modules will vary with the number of capacitors inside the module. They will also vary greatly with duty cycle.

Capacitor Estimate

Cost-per-farad values are expected to vary with production quantity as shown in Figure 14. These rates pertain to capacitors ranging from a few hundred to a few thousand farads per capacitor cell. These quantities may be associated with the program phases: prototype, low rate production, and full production. The costs apply to the total number of cells to be used in the design. Each cell will be designated with the number of farads it provides. For example, ten cells that each provide 2500 farads, in low volume production, would cost 10 x 2500 x $0.03, or $750. The cost of $.01 per farad has been mentioned as the value at which the auto industry could economically embrace capacitor technology.

Program Phase	Quantity	$/farad (2003$)
Prototype	10	0.06
Low Volume Production	1000	0.03
Production	50000	0.01

Figure 14: Individual Ultra Capacitor Cell Cost

Capacitor Module Estimate

Figure 15 illustrates the cost of designing and producing a capacitor module to house and control a number of capacitor cells. These factors are based on discussions with capacitor manufacturers and integrators. For example, building a prototype capacitor module to operate in a hybrid electric vehicle will cost an additional 160% beyond the cost of the prototype capacitor cells. The figure shows that costs for the packaging vary with the severity of the duty cycle. Engine starter duty is a light duty cycle. Hybrid duty, applicable to the systems in this report, is the heaviest tasking. The general duty cycle covers moderate use, more frequent and prolonged than the starter cycle.

Duty Cycle	Prototype	Production
Hybrid Electric Vehicle	160%	40%
General Use	100%	25%
Engine Starter	60%	15%

Figure 15: Ultra Capacitor Module Integration Cost Factors

Flywheels

A flywheel is a device for storing energy in a rotating mass. Flywheels have been used in various forms for centuries, and have a long history of use in automotive applications. Early cars used a hand crank connected to a flywheel to start the engine, and all of today's internal combustion engines use flywheels to store energy and deliver a smooth flow of power from the abrupt power pulses of the engine. Flywheels store kinetic energy within a rapidly spinning wheel-like rotor or disk. Ultimately, flywheels could store amounts of energy comparable to batteries. They store energy more efficiently than rechargeable chemical batteries with less weight and a much higher projected cycle life, making them candidates for transportation, utility service, and space applications. Specifically, flywheels may someday be used as energy storage systems on hybrid electric vehicles. Some advantages of flywheels over batteries as energy storage devices include greater power to weight ratio, more discharge/recharge cycles, operation without using hazardous materials, and lower influence of temperature changes.

Flywheels could be used in HEVs in several ways, all of which exploit the ability to deliver very high power pulses. One concept combines a flywheel with a standard engine, providing a power assist. Another concept employs a flywheel to load-level chemical batteries. Still another uses a large or multiple flywheels to replace chemical batteries entirely (in some uses, a flywheel is referred to as an "electromechanical battery"). For flywheels to have success in HEVs, however, they would need to provide higher energy densities than traditional flywheels.

The recent development in flywheel technology has promised a compact, light-weight energy storage system that needs little maintenance. Flywheels sized for use in HEVs have been prototyped and a turbine-flywheel power train was successfully road tested. There have been limited uses in some bus applications.

Current costs make competing with existing energy-storage technologies exceedingly difficult. In addition, the cost and complexity of providing sufficient containment to operate the flywheels with reasonably large factors of safety further reduce the competitiveness of this technology. Current flywheels are still very complex, heavy, and large. Safety issues have not been completely resolved and more work needs to be done to make flywheels safe and effective for HEV automotive applications.

There are two flywheel development programs that are worthy of mention. The first is a program being conducted by The University of Texas Center for Electromechanics (UT-CEM)[10]. Although the primary focus of this study is on the uninterruptible power supplies (UPS) market, it is based on an earlier effort in developing a flywheel for a transit bus system. The flywheel being developed is a 250 kilowatt system with a 2 kilowatt-hour energy storage capability.

The other development program is being conducted by Pentadyne Power Corporation, based in Chatsworth, California. Their flywheel is a 120 kilowatt unit with 0.67 kilowatt-hours energy storage capability. The company's current market is for UPS customers, but the flywheel developed for the UPS was initially intended for the urban or truck applications.

Fuel Cells

Fuel cells are being touted as the future of the automotive industry. They produce near zero emissions and are more efficient than other technologies that rely on direct combustion. The technology utilizes the chemical energy of hydrogen and oxygen to generate electricity. While not as fully developed as hybrid electric vehicle technology, significant investments are being made to develop a wide variety of fuel cell electric vehicle options. For example, in his recent State of the Union address, President Bush promised to spend $1.7 billion over five years for fuel cell research. The proposal includes $720 million in new spending, in addition to $1 billion already budgeted for hydrogen and FreedomCAR programs. Through partnerships with the private sector, the hydrogen fuel initiative and FreedomCAR aims to make it practical and cost-effective for large numbers of Americans to choose to use hydrogen fuel cell vehicles by 2020.

The world's major automobile and heavy-duty vehicle manufacturers are now engaged in efforts to commercialize fuel cell vehicles. Daimler-Benz, General Motors, Honda, Nissan, Chrysler, Volkswagen, Volvo, and others are using Proton Exchange Membranes (PEM) made by Ballard Power Systems, Inc. for research in zero-emission vehicles. PEM fuel cells are the most common catalyst in vehicle fuel cells.

Fuel cell technology poses many challenging technical issues for industry, including reliability and durability, power output, manufacturing infrastructure, hydrogen related

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[10] The Flywheel Battery Commercialization Study (1999), published by the Electric Power Research Institute (EPRI)

issues, and cost. Each of these is crucial to the development of fuel cell technology for military vehicles. Testing of fuel cells for automobiles indicates they start losing efficiency and break down after about 1,000 hours - or about 20,000 miles - of use. 5,000 hours - 100,000 miles - is required to match the current life of automobiles. With regard to power output, about 175 cells are required to generate 75 kilowatts, which equals the 100 hp produced by a four-cylinder internal combustion engine. Fuel cells need to become more efficient to reduce the number needed, and thereby reduce cost. However, there are no machines capable of mass producing fuel cell stacks in the quantity and at a speed that would enable high-volume production. Additionally, the success of fuel cells relies upon the success of hydrogen production, storage, and transportation and use.

Chapter 4 – Power Train Components

Hybrid electric vehicle power trains represent a significant departure from conventional automotive power trains. The conventional power train carries power from the internal combustion engine to the wheels or tracks. Figures 2 and 3 in Chapter 2 illustrate the arrangement of components for the series and parallel hybrid electric systems. These components are in varying stages of development and production. While these components are not fully developed, they do not present nearly the obstacle to marketization of hybrid electric vehicles that energy storage components do. Many of the components are variations on existing technology, rather than entirely new technologies. However, because the technologies are different from those used on conventional automotive power trains, data on components specific to hybrid electric vehicles is limited.

This chapter describes the components and provides estimating relationships. The components discussed include motor/generators used in the series design, the power inverters/controllers used in both designs, the hybrid transmission used in the parallel design, engines, and off-board power generation.

Motors

Electric motors are used to supplement or replace mechanical drive components. Typically a motor is coupled with an inverter, a controller, and reduction gearing. Through the controller, a motor's function can be changed to that of a generator. A single model of motor may appear in two places in a design, once as a generator and once as a motor. It is also possible that a single motor could perform alternately as a motor and a generator. This would occur when a drive motor is used in regenerative breaking. The controller switches the motor functions as required. While a wide variety of motors exist, two types are analyzed here: permanent magnet and AC induction. AC induction motors are used more frequently than permanent magnet motors. Switched Reluctance motors are also used on hybrid electric vehicles, but are not used as widely as either AC induction or permanent magnet motors, and are not analyzed here.

Methodology

The motor estimates are based on power, with kilowatts being the unit of measure. In all cases but one, this represents the peak kilowatt output. In one case, prototype motors, costs are estimated using both peak power output and continuous power output.

Data

The data for the prototype and production CPERs motors comes from a report for the California Air Resource Board (CARB) by the Institute of Transportation Studies (ITS)[11].

[11] Lipman, Timothy E., *The Cost of Manufacturing Electric Vehicle Drivetrains*, Report for the California Air Resources Board, May 1999.

The prototype costs represent actual costs of existing motors. The production costs are estimates based on material costs and an estimate for the cost of adding value to materials and for costs of labor and overhead. The data for motor development costs comes from discussions with TARDEC engineers.

Estimates

The estimates are broken down by life-cycle phase. The least data is available for motor development. Data was available for prototype motors that allowed the development of a statistical model. The CARB ITS study developed production estimates for motors, and we determined that insufficient new data was available to improve upon these estimates.

Prototype

The CPER for prototype motors is based upon data from the CARB ITS study. Cost is estimated as a function of peak and continuous power. The CPER provides rough order magnitude prototype costs. The data represents the costs to purchase single unit motors from several manufacturers. The CPER statistics are displayed in Figure 16.

CPER Equation				
Cost = 3425 + (-180.9) * kW-peak + 470.7 * kW-cont				
Definitions				
Cost	List price (in 1997 $)			
kW-peak	Peak power			
kW-cont	Continuous power			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	3425.26	1092.54	3.14	
kW-peak	-180.86	40.56	-4.46	
kW-cont	470.73	68.53	6.87	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
82.71	2461.68	15	12	+87.57%, -109.19%

Figure 16: Motor Prototype CPER Statistics

Production

Production estimating equations for motors are taken directly from the CARB ITS article. There is insufficient data to update their equations. The costs are estimates based on material costs and estimates of the cost to add value to materials and costs of labor and overhead. There are separate equations for permanent magnet and AC induction motors. For permanent magnet motors there are separate equations for production quantities of 2,000, 20,000, and 200,000 per year. AC induction motors are assumed to be developed enough that there is no quantity effect on cost. The equations are shown in Figure 17.

Motor Type	Quantity per Year	Unit Cost (BY 1997$)
Permanent Magnet	2,000	UC = 779 + 29.7 * kW-peak
Permanent Magnet	20,000	UC = 89 + 14.1 * kW-peak
Permanent Magnet	200,000	UC = 12.5 * kW-peak
AC Induction	All	UC = 540 * (kW-peak/50)

Figure 17: Motor Production Cost Equations (BY 1997$)

Development

Development cost data for motors is limited. The motor at the wheel station is typically packaged with a controller, power inverter, and reducing gears. A current estimate for the development of a motor, the gearing, its controller, and the inverter is $100k, $200k to build the first prototype, and another $100k to test the prototype in a laboratory. In development, the controller is the most expensive item to build, whereas in production the motor is most expensive. This information is displayed in Figure 18.

Pre-Production Phase	Cost ($) (BY 2003)
Component Development	100,000
Prototype	200,000
Developmental Test	100,000

Figure 18: Motor/Generator Costs

Inverters/Controllers

Inverters are devices that change power between alternating current (AC) and direct current (DC). Generators produce AC, but power stored in batteries or capacitors must be DC. However, power used at the drive motors must be AC. Thus, inverters are an integral component of a hybrid electric drive train. They are placed at the output of vehicle generators and again at the input to motors. Through the use of an electronic controller, a single inverter can convert power from AC to DC and vice versa.

Controllers are computers that use an array of sensors to detect vehicle conditions and alter motor performance to respond to driver or system demands. The hardware is mature, although redesigning and repackaging for specific functions can be expensive. Software development is the major expense in new controllers. Controllers generally appear in two applications: component control and management of the components that make up an HE system. Examples of components that use a controller are motors inside an HE transmission, motors in an active suspension unit, and drive motors for vehicle mobility. The controller and motor may be packaged together, along with the inverter. Controllers used to manage the HE system are stand-alone hardware.

Data

The data for the inverter/controller CPER also comes from the CARB ITS[12] study and conversations with industry representatives. The CARB ITS study provides data for the prototype and production CPERs. Production data represents estimates based on material costs and estimates for the cost of adding value to materials and for the cost of labor and overhead. Prototype data represents actual costs of motor inverters/controllers. The data for other component controllers, system level controllers, and development costs were provided by industry representatives.

Estimate – Motor Controllers/Inverters

A difficulty in pricing inverters and controllers is that they may be used as stand-alone components or as part of a set, consisting of a controller, an inverter and a motor. Further, off-the-shelf components are used in today's proof of concept demonstrations. Components are often oversized and mismatched, so data from programs may not reflect future costs. New designs that optimize space and performance will be part of future HE vehicle programs. The complexity of the functions governed by controllers varies widely, so pricing without knowing the specific application is an approximate process.

Prototype

The CPER developed for prototype motor controllers/inverters is based upon data from the CARB ITS article. This estimate bases the cost on weight. This equation can provide a rough order magnitude of prototype costs. The data represents the costs to purchase single unit controllers/inverters from several manufacturers. The CPER statistics are displayed in Figure 19.

CPER Equation				
Cost = 2441.11 + 114.17 * Wt				
Definitions				
Cost	List price (in 1997 $)			
Wt	Controller/Inverter Weight			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	2441.11	687.22	3.55	
Wt	114.17	10.84	10.54	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
94.83	1185.58	7	5	+23.79%, -16.86%

Figure 19: Controller/Inverter Prototype CPER Statistics

[12] Lipman, Timothy E., May 1999.

Production

Production estimating equations for motor controllers/inverters are taken directly from the CARB ITS study. The data represents estimates based on material costs and estimates for the cost of adding value to materials and for the cost of labor and overhead. Insufficient data is available to update these CPER. These are separate equations for permanent magnet and AC induction motor controllers/inverters. For each type, there are separate equations for production quantities of 20,000 and 200,000 per year. The equations are shown in Figure 20.

Controller/Inverter Type	**Quantity per Year**	**Unit Cost (BY 1997$)**
Permanent Magnet	20,000	UC = 392 + 9.44 * kW-peak
Permanent Magnet	200,000	UC = 262 + 6.94 * kW-peak
AC Induction	20,000	UC = 418 + 10.76 * kW-peak
AC Induction	200,000	UC = 312 + 7.6 * kW-peak

Figure 20: Controller/Inverter Production Cost Equations (BY 1997$)

Estimate – Other Controllers

Data for other types of controllers is limited. Insufficient data exists for the development of robust statistical models. The rough costs displayed in Figure 21 were developed from manufacturer estimates. These estimates represent production items, generally applicable to hybrid electric vehicle systems, but not configured specifically to any one vehicle.

Production Quantity	<10	>100
Controller Function:	**Unit Cost ($)**	**Unit Cost ($)**
Battery Pack	1,700	1,100
Vehicle	4,000	2,500
Engine/Generator	15,600	9,800

Figure 21: Controller Costs for System and Components (BY 2003$)

Controller development

The data for controller development costs is anecdotal. Insufficient information exists to develop robust statistical models. However, the available data are provided as cost guidelines. This provides benchmarks for the development of component and vehicle controllers. It also covers the cost of developing a new technology based on existing technology, as well as the cost to integrate multiple controller/inverter/motor sets.

An effort to design and build a controller for an engine and generator is estimated to take 12-18 months and 3-5 full time equivalent employees (FTE). A controller for a motor alone takes 9 months and 2-3 FTE.

An estimate for the cost to go from a component now in production now to a new component with better power density, is that the production cost of the new replacement component would be double that of the current component.

The effort to integrate two or more sets of controllers, inverters and motors is estimated to take at least 5 to 10 times the cost of the components.

Development time for a controller of a new engine going into a HE system is estimated to be about 2 years and 3 FTE, or about $1.2M plus material. This assumes the engine manufacturer cooperates with the company designing the controller. Otherwise, the process is slower with poorer results. Tasks being accomplished in this estimate are mechanical interfaces, software, and electronics.

Development of a vehicle controller is estimated to take 2 years and 6-8 FTE, depending on the complexity and whether the components are familiar or not. If the vehicle is highly specified, i.e., a military vehicle, then it could take 8 to 10 FTE over two years.

Transmissions

Hybrid electric transmissions are used in the parallel design. Allison appears to be the only manufacturer of this type of transmission suitable for military vehicles. As currently configured, the transmissions contain two motor generators and their controllers. The transmission is sold and installed as part of a package, not as an individual item. Components include a pair of controllers (one monitors the two drive motors inside the transmission and a second monitors the engine and vehicle functions) and a NiMH battery pack. This pack is manufactured by PEVE, the Panasonic-Toyota consortium that builds the battery pack in the Toyota Prius. The final component is a Dual Power Inverter Module, which converts AC to DC and vice versa as needed.

The Allison EV40 is an electric transmission currently used on HE buses in New York City. A contract to buy 325 buses using this transmission will be accomplished in 2003. Rough prices are available for the transmission set, but not the individual components. Figure 22 shows the Allison EV40 and EV50 transmissions and a purely notional HE

HP Ratings	**Allison EV 40**	**Allison EV 50**	**Notional combat vehicle HE Transmission**
Transmission Continuous Load	280	330	500
Engine + Battery Acceleration	350	400	600
Dual Power Inverter Module	440	440	600

Figure 22: Actual and Notional HE Transmissions

transmission for a combat vehicle. The EV 40 and EV50 appear to use the same transmission and power inverter. Electronic components internal to the transmissions differ somewhat to accommodate the different power input levels.

A transmission to be used in a combat vehicle would be sized for a 500 hp engine or larger. This would require the use of a different transmission than used in the Allison EVs, which would have to be modified with a new set of motors and controllers. The Dual Power Inverter Module would require a third inverter. The energy storage capacity of the battery pack would increase in size to provide a proportionally similar boost to the engine as is seen in the EV40 and EV50 applications. Reengineering for more constrained vehicle space would be expected to increase prices, too.

Allison cited a rough order of magnitude cost of $140,000 for the EV 40 going into the NYCTA buses, and noted that there was some cost sharing on their part. They also indicated that a military version may cost 3 to 5 times that of a conventional drive. Realistic prices for the production of a military application of the transmission could be above $200,000. A low rate initial production military transmission could cost $300,000.

Engines

HE vehicles use the same type of ICE that a conventional vehicle uses. The advantage of HE vehicles is that this engine can be downsized, because the battery-powered electric motor supplements the engine. Thus, an HEV can obtain the same power output as a conventional vehicle using a smaller engine. This is important for a number of reasons. First, it increases the fuel economy of a vehicle for given power output. Second, it decreases the emissions from the power train. Finally, reducing the size of the engine offsets some of the weight gain caused by the battery pack.

In many military applications, however, the goal is not to achieve the same power with a smaller engine, but rather to use the electric motor to provide a power boost. Thus, more power can be achieved without having to increase the size of the engine. In this case, the gain in fuel economy and the emissions decreases are negligible. Further, there is no weight reduction to offset the large battery pack. Thus, additional measures must be undertaken to reduce the weight of the vehicle. One such measure is to design engines that offer the same power outputs, but at significantly reduced weights. These “high power density” engines are currently in development and insufficient data currently exists to estimate their cost. In this report are provided estimates of conventional engine technology. This allows for estimates of engine costs in cases where the engine is downsized and current generation technology is used.

Data

The data used to develop the CPER represents current generation engine technology. The CPER can be used in cases where the new high power density engines are not used. This situation would occur when the engines are downsized in order to accommodate a larger battery pack. The data comes from the Wheeled and Tracked Vehicles Database.

Methodology

Engine costs are estimated as a function of power output, measured by horsepower. These are valid estimates current generation engine technology, but not for newer high power density engine technology.

Estimate – Current Generation Engine Technology

The estimates for conventional technology are based upon horsepower. The CPER statistics are displayed in Figure 23, and the data is graphed in Figure 24.

CPER Equation				
Cost = -(109.64) + 22.96 * ln(hp)				
Definitions				
Cost	Unit Cost (BY 2000 $K)			
Ln(hp)	Natural log of horsepower			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	-109.64	6.31	-17.39	
Ln(hp)	22.96	1.08	21.11	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
98.89%	1.29	6	4	+5.23%, -5.8%

Figure 23: Engine CPER Statistics

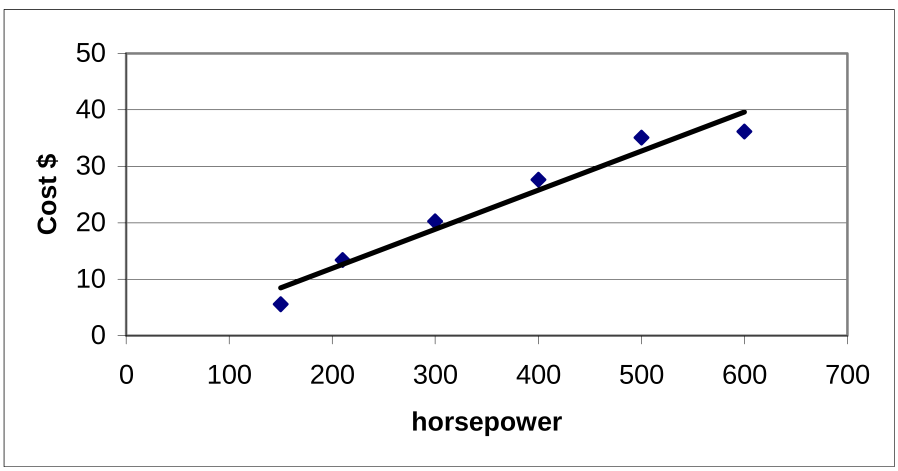

Figure 24: Engine CPER Costs v. Horsepower Plot

Off-board Power Generation

A potential feature of HEVs is off-board power generation. The vehicle can be used to provide power to other vehicles and systems on the battlefield. While HEVs are not likely to replace field generators altogether, they do allow a quick deployment capability. HEVs can be used as initial power sources while other assets are moved into place.

Data

The data collected for this CPER represent generators similar in style to that used on a current tactical vehicle demonstrator program. The data comes from one manufacturer. The dataset provides a wide range of power, with 122 kW being the smallest generator and 1790 kW being the largest generator. It represents list prices, so costs are likely to be maximums. Quantity buys would be negotiated at lower rates.

Methodology

Costs are estimated as a function of power, with kilowatts as the unit of measure.

Estimate

Power is a good predictor of generator costs. The results of the CPER are displayed in Figure 25. Figure 26 shows a graph of the data.

CPER Equation				
Cost = 3009.10 +23.920 * kW				
Definitions				
Cost	List price (in 2003 $)			
kW	Kilowatt rating			
Variable Statistics				
Variables	Coefficient	Std. Deviation	T-statistic	
Intercept	3009.10	300.61	10.01	
kW	23.92	0.40	60.36	
Model Statistics				
R^2 Adj	Std. Error	Observations	Degrees of Freedom	Fit Range
99.16%	939.90	32	30	+3.68%, -1.64%

Figure 25: Off-Board Power Generation CPER Statistics

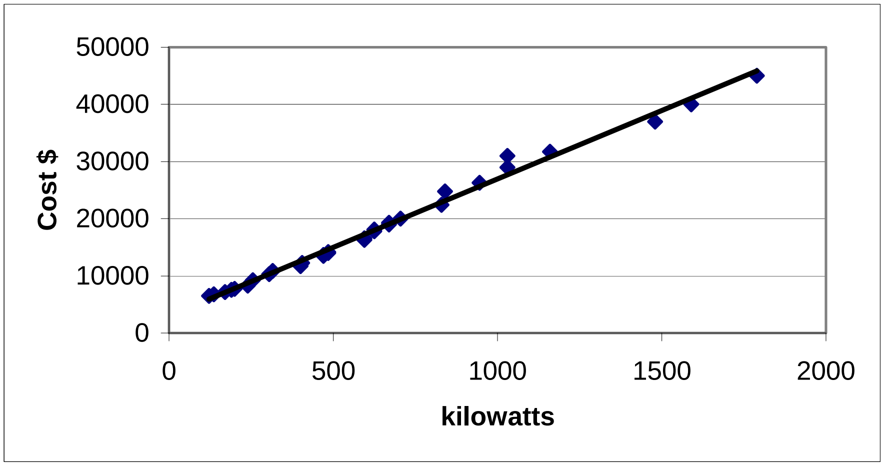

Figure 26: Off-Board Power Generation Costs v. Kilowatts Plot

Chapter 5 – Electro-magnetic Armor

Electro-magnetic armor (EMA) systems use a very high current to disrupt the jet of a chemical warhead. This technology replaces some of the heavier conventional armor on combat vehicles. It is well suited to hybrid electric vehicles (HEV) where some of the HEV infrastructure can support the electrical system of the EMA.

The battery pack of the HE vehicle can be used to charge a pulse forming network (PFN). A capacitor module in the PFN stores up to 100 - 200 kilojoules of energy. The armor is triggered by the impact of a chemical warhead plasma jet. At this point, the stored energy is dissipated extremely quickly in a controlled and shaped pulse. The current disrupts the jet, severely limiting its ability to penetrate the vehicle.

Technical challenges to successful EMA development include the following: light-weight battery banks; flywheel energy storage; high capacity, high energy-density conventional polymer capacitors; low impedance busses; and high current, high firing-rate switches. All components are well along in development. System tests have shown very good success at reducing jet penetration, and system integration issues are being addressed.

The cost estimate developed for the electro-magnetic armor system is considered proprietary information because of the lack of competitive sources working in this area. Future solicitations for the development and production of EMA are expected and cost estimates based on the current development effort could influence the proposals of potential bidders. It is the government's intention that the current estimate not be made available outside the government.

A copy of the estimate, for distribution only to government agencies, is available through the Defense Technical Information Center.

Section III – Additional Considerations

Chapter 6 – Operation & Sustainment

Operation and sustainment (O&S) costs are an important part of the evaluation of any new program. In a situation where the technology is new, as with HE systems, reliable estimates are difficult to develop. At present, there are no fielded military vehicles currently using HE systems. There are, however, commercial market examples that shed light on the potential O&S costs for hybrid electric vehicles. Additionally, there have been analyses of military vehicles to determine the conditions necessary for hybrid vehicles to "break-even," i.e. cost no more than the current vehicle configurations. All current analyses cast doubt on the idea that hybrid vehicles will provide cost savings.

Three sources of information that pertain to O&S costs were reviewed for this report. The first is an Argonne National Laboratory (ANL) study that modeled future O&S costs for commercial hybrid electric vehicles relative to conventional vehicles[13]. The second study is a Department of Energy/National Renewable Energy Laboratory Transit Bus Evaluation Project analysis of hybrid electric transit buses in New York City[14]. The third study is a Logistics Management Institute (LMI) analysis of the lifetime costs and savings of the hybrid HMMWV and the Commercially Based Tactical Truck (COMBATT)[15]. The results of each of these studies are analyzed separately. Each illustrates the difficulty hybrid vehicles face with regard to providing operating cost savings.

Commercial Vehicle O&S Costs

The ANL study models the future costs of commercial hybrid electric vehicles relative to conventional vehicles. While O&S costs per mile tend to be significantly lower for commercial vehicles relative to military vehicles, important insight can still be obtained by examining commercial markets. Several different scenarios are analyzed in the study, including parallel, series, full-hybrid, mild-hybrid, and full electric configurations. In addition, costs are projected with and without a battery replacement within the vehicle's lifetime. The configuration focused upon here is a hybrid series configuration with one battery replacement.

Figure 27 illustrates the future O&S costs modeled by ANL. These factors represent the ratio of hybrid vehicle O&S costs to conventional vehicle O&S costs. The figure shows three curves, each representing different zero-to-sixty mph performance times. The figure indicates that even out to 2020, hybrid electric vehicles are projected to remain

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[13] Plotkin, S., D. Santini, A. Vyas, J. Anderson, M. Wang, J. He, and D. Bharathan, *Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results*, Center for Transportation Research Argonne National Laboratory, October 2001.

[14] Chandler, Kevin, Kevin Walkowicz, and Leslie Eudy, *New York City Transit Diesel Hybrid-Electric Buses: Final Results*, DOE/NREL Transit Bus Evaluation Project, July 2002.

[15] Canes, Michael E., *Economics of Hybrid Electric Technology: Military Vehicles*, Logistics Management Institute, September 2002.

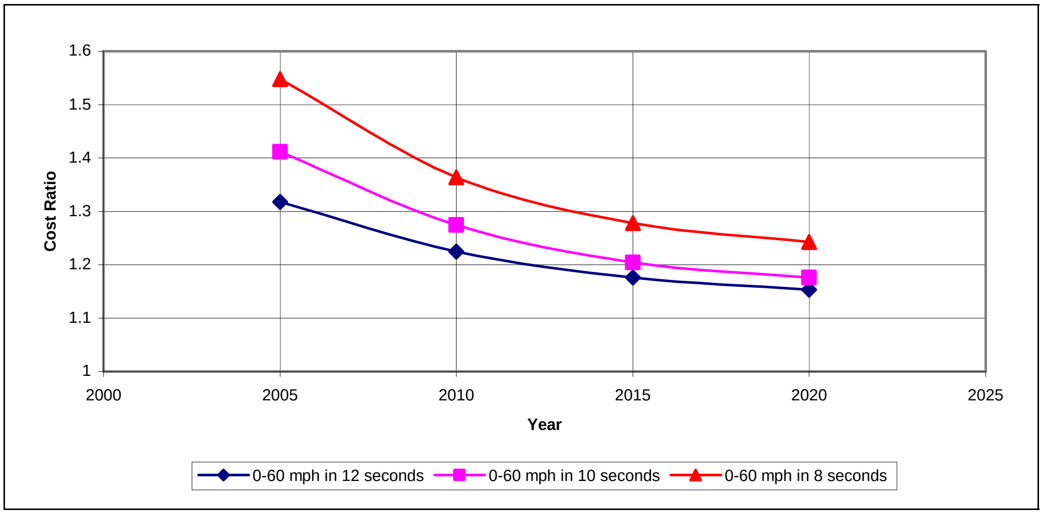

Figure 27: Ratio of Hybrid Electric to Conventional Drive Train O&S Costs

more expensive to operate than conventional vehicles. This analysis takes into account the significant fuel savings that occur by converting to hybrid technology. These fuel savings relative to conventional vehicles increase as the performance of the vehicle improves. However, the non-fuel costs and battery costs outweigh the savings generated by increased fuel efficiency. Battery costs, in particular, increase significantly as vehicle performance improves.

New York Transit Bus O&S Costs

The study of New York transit buses provides real-world data with regard to the hybridization of a vehicle fleet. This study's results are limited in the sense that the vehicles analyzed are prototypes and the environment is not analogous to a military environment. However, the vehicles are closer in terms of weight to military vehicles than those analyzed by ANL. The study analyzes the operation and sustainment costs of four types of buses over the period from July 2000 to September 2001. The buses analyzed are four NovaBus RTS diesel bus from the Manhattanville (MV) Depot, seven Orion V diesel buses from the Amsterdam (AMS) Depot, and two groups of Orion VI hybrid buses, an older group of four buses and a newer group of five buses. The latter two were separated to analyze improvements made in the technology. The MV buses were chosen because their chassis was built by the same manufacturer in nearly the same model year as the hybrid buses. However, they had a different duty cycle. The AMS buses were selected for comparison because they shared a duty cycle with the hybrids, although there are significant chassis differences between the two.

The cost factors that the study reported are shown in Figure 28. They show that while the newer hybrids are cheaper to maintain than the older hybrids, both are significantly more expensive than the conventional diesel buses. While the cost per mile is likely to be significantly lower than in a military environment, the ratios provide insight into the operating costs of a hybrid vehicle fleet.

	Operating Cost	Ratios (Column system is numerator, row system is denominator)			
	($/mile)	Old Hybrid	New Hybrid	MV	AMS
Old Hybrid	2.286	-	0.7651	0.5241	0.4764
New Hybrid	1.749	1.307	-	0.685	0.6226
MV	1.198	1.9082	1.46	-	0.909
AMS	1.089	2.0992	1.6061	1.1001	-

Figure 28: New York City Transit Authority Bus Fleet O&S Comparison

Military Vehicle Break-even Costs

The LMI study analyzes the life-cycle costs of hybrid and conventional versions of two military vehicles, the HMMWV and the Commercially Based Tactical Truck (COMBATT). The study uses some basic assumptions about the vehicles, their performance, and the way they are operated to produce initial results. It is assumed that the initial costs of hybridization are equal to the savings resulting from the reduced need for power generators. Only fuel and battery costs are analyzed, and maintenance costs are ignored. The author assumes that the costs to maintain the new hybrid components will be equal to the savings from using regenerative braking and maintenance of generators. This is an open question, however, as both the ANL and New York City studies show significant non-fuel costs for hybrid vehicles over those of conventional vehicles. On the other hand, commercial vehicles markets do not realize cost savings as a result of the power generation abilities of hybrid electric vehicles.

For analyzing the HMMWV, the study chooses a base set of assumptions. They are

- The vehicle has a lifetime of 20 years.
- The fuel cost to the Army is $10 per gallon.
- Batteries last for 3 years and have a replacement cost of $3,000.
- The fuel efficiency gain is 30 percent.
- A conventionally powered HMMWV gets 9 mpg and is driven 3,500 miles per year.
- The discount rate is 6%.

Using these assumptions, the Hybrid HMMWV is slightly less expensive to maintain than a conventional HMMWV. The Net Present Value of the savings over the life of the vehicle is approximately $90.

For analyzing COMBATT, the study chooses a base set of assumptions. They are

- The vehicle has a lifetime of 15 years.
- The fuel cost to the Army is $10 per gallon.
- Batteries last for 3 years and have a replacement cost of $3,000.
- The fuel efficiency gain is 20 percent.
- The base fuel efficiency for a non-hybrid COMBATT is 14 mpg
- The vehicle is driven 5,000 miles per year.
- The discount rate is 6%.

Using these assumptions, COMBATT is significantly more expensive to maintain than a similar non-hybrid vehicle. The Net Present Value of the cost over the life of the vehicle is approximately $2,119.

Summary

These studies illustrate that hybrid electric vehicles may not be developed to the point that they provide significant life-cycle cost savings over conventional vehicles. While they do provide fuel savings, the cost of batteries and the cost to maintain other components cause the overall costs to be higher than those of conventional vehicles. However, as the technology matures, these costs are likely to fall, improving the case of hybrid vehicles. For now, proponents of hybrid electric vehicles will have to point to factors other than maintenance costs to make the case for hybridization. These arguments in a military environment include improved operational capabilities, enhanced power generation, and a potential to reduce the logistics footprint. It should be noted that the New York City Transit Authority has submitted an order for an additional 325 buses, despite the apparent lack of savings.

Chapter 7 – The Status of HEV Development and Future Effort

This study provides CPERs for hybrid electric components. The information contained in this report represents the current state of technology, but this could change rapidly. Many major components are still developing; major breakthroughs could occur; or technology that is expected to evolve could falter. Additionally, the success of hybrid electric vehicle technology relies on, among other things, greater acceptance of the technology by commercial market automobile consumers and significant government and private sector investment. These could lead to significant cost reductions that make the technology more affordable to the military.

Hybrid electric vehicles are viewed largely as a transition to fuel cell technology. If fuel cell technology progresses faster than expected, continued development of hybrid electric vehicles could falter. Thus, it is important that these relationships continue to evolve. As the technologies mature, cost and performance will change in ways that could not have been predicted. Therefore it is important that these cost relationships be updated to keep pace with technological changes within the industry. This will ensure that these relationships remain relevant into the future.

One area that will be particularly important to pursue further is system integration. Data on system integration is difficult to find. The US Army's National Automotive Center (NAC) sponsored three prototype development efforts under a Hybrid Electric Combat Vehicle Program Study. Extracts from the NAC descriptions of these programs are provided below. These programs could provide information in the future on system integration costs.

M113 HE Transformation Technology Demonstrator (M113 TTD)

The M113 TTD tracked vehicle is a series configuration. There was no component redesign required for this program. It utilizes two 250 horsepower motors and three oil cooled inverters, one for each motor and a braking inverter to support regenerative braking. The transmission has been removed. Commercial equipment has been utilized for the motors, inverters and controller, and the batteries are standard lead-acid. During tests at Aberdeen Proving Ground over multiple terrains, the M113 HE demonstrated a fuel efficiency gain of 16-36%. The estimated cost of the standard propulsion system for the M113 is $125,000. The estimated cost of the M113 HE propulsion system is $250,000. The contractor performing the modifications is UDLP. The total investment in the project was $4 million co-funded equally by the NAC and UDLP.

Light Armored Vehicle (LAV) & Civilian Heavy Hybrid

A Light Armored Vehicle and a Mack Refuse hauler were selected to test a GM Allison parallel hybrid electric drive. This summary will focus on the LAV only, although both programs were executed successfully. The Allison system selected was the second generation EP 50 operating in conjunction with the LAV standard Caterpillar 350 engine.

There was no component development on this project. The EP 50 replaced the transmission in the LAV. It was a drop-in installation in the space formerly occupied by the transmission. Additional battery packs were also added. Initial testing did not demonstrate any significant fuel efficiency improvement although the vehicle was not subjected to any rigorous testing process. The project contractors were Allison Transmission, Electricore and GM Defense plus Mack Truck on the commercial vehicle. The total investment in the project was $4.2 million co-funded equally between the NAC and the contractors.

Advanced HE Technology Demonstrator (AHED)

This vehicle was new from the ground up, not the result of upgrading and modifying an existing vehicle. The objective was to demonstrate in-hub electric wheel drive technology and the significant design, integration and performance benefits that can be realized by utilizing this technology for medium/heavy class wheeled vehicles. The resulting vehicle was an 8x8, approximately 20 ton unit utilizing a series HE propulsion system. Additional technologies implemented in the vehicle include a Lithium-Ion battery pack, Hybrid Steering (Ackerman and skid), independent height adjustable air suspension, and an aluminum chassis. The wheel motors are 150 HP. The contractor was General Dynamics. The total investment in the project is $16 million that was co-funded by the NAC and General Dynamics. No additional pricing information on components or design is available.