Powertrain Technology and Cost Assessment of Battery Electric Vehicles

by

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Abstract

This thesis takes EV from the late 90's as a baseline, assess the capability of today's EV technology, and establishes its near-term and long-term prospects. Simulations are performed to evaluate EVs with different combinations of new electric machines and battery chemistries.

Cost assessment is also presented to address the major challenge of EV commercialization. This assessment is based on two popular vehicle classes: subcompact and mid-size. Fuel, electricity and battery costs are taken into consideration for this study. Despite remaining challenges and concerns, this study shows that with production level increases and battery price-drops, full function EVs could dominate the market in the longer term. The modeling shows that from a technical and performance standpoint both range and recharge times already fall into a window of practicality, with few if any compromises relative to conventional vehicles. Electric vehicles are the most sustainable alternative personal transportation technology available to-date. With continuing breakthroughs, minimal change to the power grid, and optimal GHG reductions, emerging electric vehicle performance is unexpectedly high.

Acknowledgements

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List of Abbreviations

A	Ampere
Ah	Amp-hour
Al	Aluminum
CARB	California Air Resources Board
Co	Cobalt
DOD	Depth-of-discharge
EPA	Environmental Protection Agency
ETS	(GM) Electric Traction System
EV	Electric Vehicle
GHG	Greenhouse Gas
GUI	Graphical User Interface
HEV	Hybrid Electric Vehicle
Li-ion	Lithium-ion Battery
Mn	Manganese
Ni	Nickel
NiCd	Nickel Cadmium battery
NiMH	Nickel Metal Hydride battery
NRCAN	Natural Resources Canada
PbA	Lead Acid battery
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State-of-Charge
SOH	State-of-Health
US DOE	United States Department of Energy
USABC	United States Advanced Battery Consortium
V	Volt
W	Watt
Wh	Watt-hour
Ω	ohm
VRLA	Valve Regulated Lead Acid battery

1. Introduction

The electric drivetrain is one of the oldest technologies and attracted renewed attention in the 1990's as California introduced strict GHG emission standards, the Zero-Emission Vehicle (ZEV) mandate. The ZEV program was strongly altered in the early 2000's, largely because EVs failed to approach performance levels of a conventional vehicle, and it was never a financially sustainable proposition for any auto manufacturer.

The industry then shifted its focus to HEVs and fuel cell vehicles, which were introduced during the late 90's and early 2000's, while EVs were phased out. The HEV technology seemed viable at that time because it offered much more flexibility from levels of hybridization to choices of architecture. Its battery pack size is small compared to an EV thus reducing manufacturing cost. The NiMH battery technology, evolved during the EV period with high specific power, was adapted and ultimately became the enabler for HEVs.

The lowest level of hybridization is the Micro-HEV. It features automatic engine start/stop operation with regenerative braking. An enhanced starter motor or an integrated starter generator can deliver the idle start/stop function; either belt-driven or crankshaft-mounted. The benefit of regenerative braking depends on the power level of the electromechanical component. A typical generator capacity for a Micro-HEV is in the range of 2-4 kW, along with the conventional 12V battery; the need for modifications to the brake system is minimal. Fuel consumption and CO_2 emissions can be reduced by 1.5-4%, depending on vehicle, drivetrain and driving conditions. [Karden, 2004]

At higher voltage levels (~42 V), limited electric propulsion assist becomes possible. Mild-HEVs offer propulsion assist at lower engine speeds only, whereas Medium-HEVs

(~144V) can support the combustion engine at higher vehicle speeds. The higher electromechanical power level also enables higher fuel saving benefits from regenerative braking. Additional mild and medium HEV features can include engine torque smoothing for shift assist. The energy storage devices of mild and medium HEVs are required to transmit more power. Also the generator of a mild and medium HEV is more powerful than that of a Micro-HEV; 110 V or 220 V AC vehicular power outlets are feasible.

Full HEVs offer strong electric propulsion assistance and pure electric driving power, but very limited all-electric travel range, if any. The electric drive line and battery typically operate at high voltages, above 200V. The Toyota Prius and Ford Escape hybrid are both categorized as full HEVs. As an example, the Ford Escape hybrid combines an efficient 2.3 liter Inline 4 cylinder Atkinson cycle engine with a 70 kW permanent magnet traction motor and 45 kW generator to operate as an electric continuously variable transmission [Karden 2006]. Full HEVs are taking a greater share in the growing HEV market in North America today. They are capable of reaching the super-ultra-low emission levels (SULEV).

Traditionally, HEVs are classified into two basic powertrain architectures, series and parallel, according to their drive line configuration.

Series Hybrid Drivetrain

The series hybrid drivetrain is the simplest kind of HEV. Its key feature is to couple the engine with the generator and produce electricity for pure electric propulsion. In a series configuration, the engine's mechanical output is first converted into electricity using a generator. The converted electricity can either charge a small battery (acting as a buffer) or bypass the battery to propel the wheels via an electric motor. It is an engine-generator powered EV which enables the driving range to be comparable with that of a conventional vehicle. The architecture is known for its flexibility in locating the engine-generator set since no clutches or mechanical linkages from it are required to the driveline. The GM upcoming Volt is the “plug-in hybrid” variant of such an implementation. Since the engine is completely decoupled from the driven wheels, the IC engine can always operate in its most efficient zone. However, because the mechanical energy from the engine first needs to convert to electrical energy through the generator and then back to mechanical again through a traction motor, energy conversion occurs twice causing multiplicative energy losses. Another tradeoff regarding the simplicity of a series drivetrain is that it needs three propulsion devices, the IC engine, the generator and the electric motor. All these propulsion devices must be sized for the maximum sustained power, for example when the HEV is fully loaded or climbing a hill. However, it is ideal for city driving where the average duty cycle is less, and the propulsion devices can then also adopt a lower nominal rating.

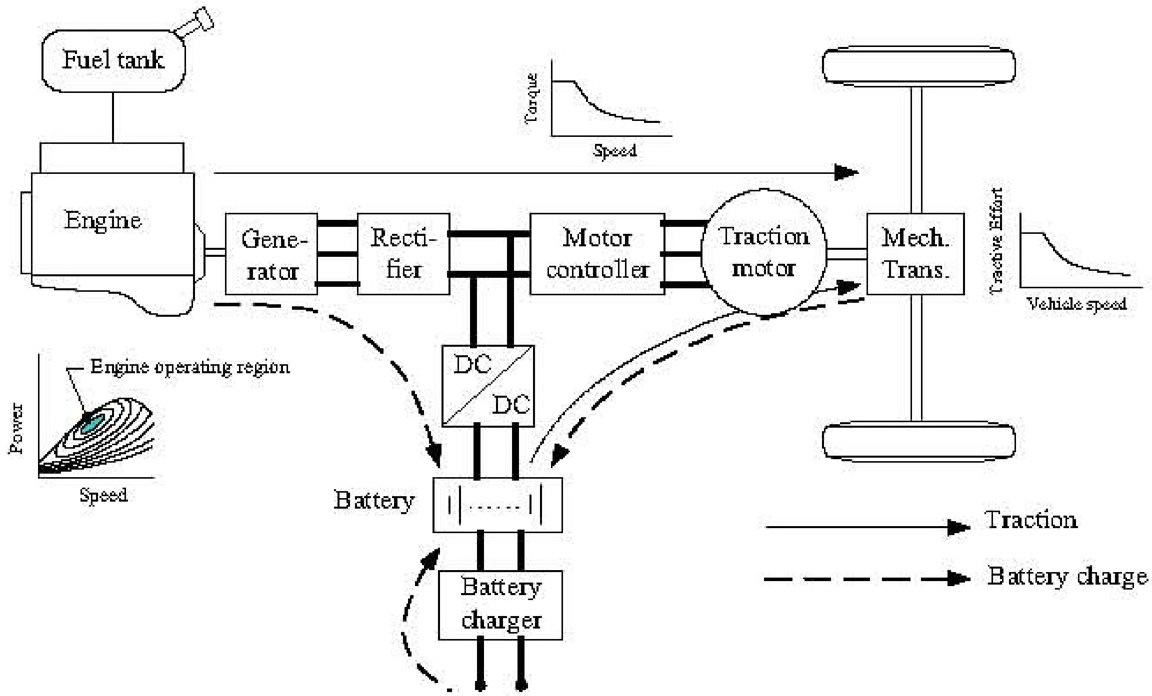

Figure 1-1, Series hybrid electric drivetrain, plug-in hybrid variant shown [Gao 2005]

This same type of drivetrain arrangement is also used in fuel cell vehicles, where the IC engine and the generator are replaced by the fuel cell.

Parallel Hybrid Drivetrain

Differing from the series hybrid, as its name suggests, the parallel hybrid drivetrain arranges the propulsion devices such that it allows both the IC engine and the electric motor to deliver power in parallel to the driven wheels. This is achieved by coupling both the IC engine and the electric motor to the drive shaft through clutches. Therefore, the propulsion power may be supplied by the engine alone, by the electric motor alone, or by the two devices together. No energy conversion is necessary in the parallel arrangement, thus energy loss is less compared to the series drivetrain. Conceptually, it is a conventional vehicle with electric assist to achieve lower emissions and better fuel economy. The electric motor in a parallel configuration can be used as a generator to charge the battery by retracting power normally dissipated during braking (regenerative braking). When the electric machine is used as a generator, it can also be driven by the engine should the engine's optimum output be greater than that required to drive the vehicle, or when the battery's state-of-charge is low. As a result, the parallel hybrid only needs two propulsion devices, the IC engine and the electric motor. Each of these can also be smaller in terms of size and the power delivered. Even for heavy duty uses, only the engine needs to be designed for maximum sustained power, while the size of the electric motor can be kept small. However, the engine is mechanically linked to the driven wheels, thus the engine's operating regime is not being restricted only to the most efficient region; and this hybrid configuration is more complex to control relative to the series configuration.

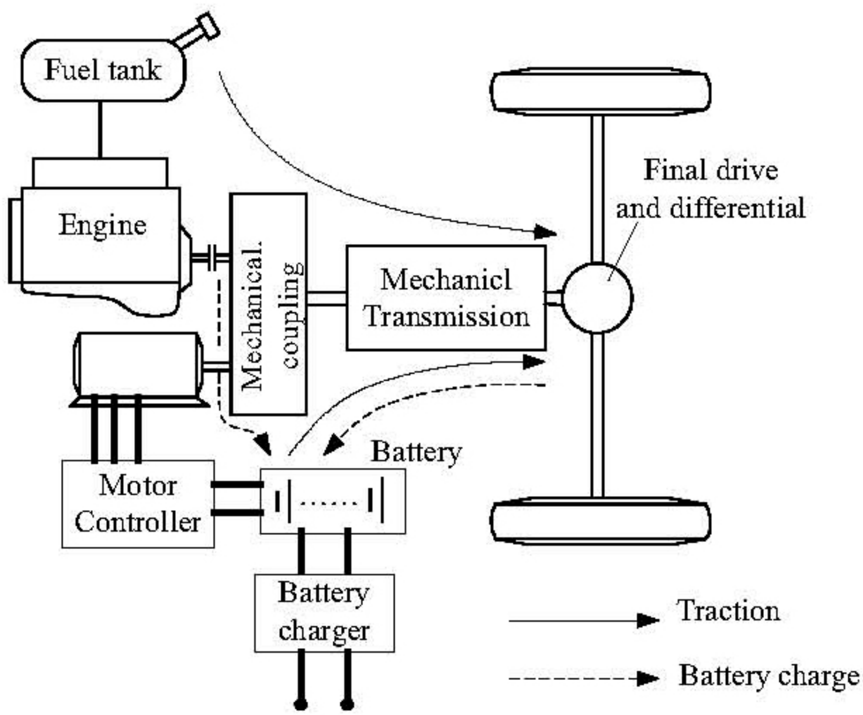

Figure 1-2, Parallel hybrid electric drivetrain, plug-in hybrid variant shown [Gao 2005]

HEVs today still use Nickel-metal Hydride batteries for their energy storage system. One step forward from HEV is the “plug-in HEV” (PHEV), which can recharge its traction battery pack from the electricity grid, displacing part of the fuel consumption, and further reduce tail pipe emissions. The PHEV has a larger battery pack compared to a HEV, and increases vehicle fuel economy by offering greater all-electric driving range; however due to battery cost, this range is rather limited for first generation PHEVs (20-40 miles). PHEVs that are soon to be introduced in the marketplace incorporate lithium based batteries. By adopting new battery chemistry and offering more significant all-electric range, the PHEV is serving as a transitional stage from HEV to full function EV.

As battery technology has drastically improved during the 10-year interlude from the last EV era, electric vehicles have gained renewed interest. EVs introduced under the original ZEV mandate were already highway capable, but early batteries degraded too fast. EV owners often needed a battery pack replacement, or service on battery modules during the life of the vehicle. Vehicles of the era were powered by lead acid and later nickel-metal hydride batteries, the former of which had poor energy density thus low vehicle range, and also short life. Full function electric vehicles need to be able to achieve a 100+ mile range for given average driving patterns and consumer expectations, according to minimum requirements set by the California Air Resources Board (CARB). Earlier generation expectations were 60 miles range, but this has now rather become an upper target for the PHEV electric range.

Goals of Thesis

This thesis work first assesses today's battery and electric machine status and performance, then performs simulations of full function electric vehicles in the mid-size vehicle class with current electric powertrain capability. The work is anchored and calibrated by using electric vehicle baselines established from previous generation drivetrain components. A cost study is done by comparing different energy storage system sizes matched to vehicle size, and assesses when / if electric vehicles will become practical by looking at total operational costs. At that point they will begin encompassing significant market share.

2. Battery Technology

Since the emergence of electric vehicles more than a century ago, the lead acid battery has been the most popular choice; it is a mature and well-understood technology. It is also relatively inexpensive and simple to manufacture but suffers from low energy density and limited cyclic life. The battery used in electric vehicles during the last 15 years has evolved from lead acid technology in the early generations, to nickel based batteries in the late 90's, switching towards lithium-ion batteries in recent years. Lithium based batteries will soon dominate the HEV, PHEV and EV markets with their superior characteristics of high energy density, power density and low internal resistance. The battery has always been the key concern weighing against electric vehicles. It is seen as too heavy, too expensive, with low cyclic life and resulting in limited driving range. Parameters defining battery performance for electric vehicles include energy density, power density, cyclic life, shelf life, initial and life cycle costs.

2.1. Lead acid battery

The lead acid battery (PbA) is the oldest secondary battery. It is widely used and still the most cost effective choice in the automotive industry. A lead acid cell can have three forms of electrolyte packaging: flooded with liquid electrolyte as in traditional lead acid batteries, "sealed" using a gelled electrolyte, or absorbed electrolyte on a glass matt for the valve-regulated lead acid (VRLA) variant. The latter two can be used in any position with no risks of electrolyte leakage or outgassing, therefore they were chosen for automotive applications in the 1990's. However, flooded batteries are more tolerant to overcharge than sealed ones. In the charged state the cathode, lead (IV) dioxide (PbO_2)

and the anode, elemental lead (Pb), are immersed in an electrolyte of sulfuric acid (H_2SO_4). When discharged, both electrodes turn into lead sulfate ($PbSO_4$). The lead acid battery is not very tolerant of deep discharge cycles. This causes capacity loss and premature physical failure. A discharged state damages the battery via crystallization of lead sulfate at the electrodes, "insulating" them by creating chemically inactive regions; the battery then loses its ability to acquire a charge.

During the 90's this technology was used in various production electric vehicles, i.e. GM EV1 (GEN I), Ford Ranger, Toyota RAV4, etc. These first generation electric vehicles employed deep-cycle lead acid batteries designed to deliver a more consistent voltage during discharge, and were able to operate down to as low as 15% state-of-charge (SOC). The optimum temperature for a lead acid battery is ~25°C. Elevated temperature reduces longevity. The need for high discharge rates is also critical for vehicle dynamic performance. Lower discharge rate produces higher apparent capacity due to the "Peukert effect", a way to model the combination of electrochemical reaction rate and internal resistance [Larminie 2003]. A high discharge rate on a lead acid battery significantly reduces vehicle range.

2.2. Nickel-based Battery

2.2.1. Nickel Cadmium Battery

The nickel cadmium battery (NiCd) uses nickel oxyhydroxide for cathode and metallic cadmium for the anode [Larminie 2003]. Its electrolyte also exists in paste and wet forms. Paste cells suffer from memory effects if they are not completely drained before recharging, which is not a suitable option for electric vehicle applications. NiCd batteries with liquid electrolyte on the other hand are very robust, and exhibit long cyclic life. This type of cell exists in large capacity formats. It performs well under deep discharge cycles, and can be charged at high current and operate through a wide temperature range, -30 to 60°C [Putois 1995]. Crystalline formation on cell plates causes capacity loss if the cell is left in a discharged state; proper maintenance such as full charge cycles can avoid this problem. Flooded cells need to be vented under charging for safe operation, but are generally not damaged by overcharge, however the electrolyte needs to be replenished. They are also less expensive than dry cells due to a simpler structure. Regular maintenance is a significant drawback, since venting of gases causes water loss in the electrolyte, which must be periodically replenished after the battery is fully charged. Properly maintained NiCd batteries can last 20 years, resulting in lower cost over the life of the battery. Even under abusive service encompassing 0% SOC storage over extended periods, and extreme environment, relatively simple recovery procedures can revive over 90% of the battery's initial capacity in many cases. Such recovery service has been performed at the UOIT Electric Vehicle Laboratory for flooded NiCd batteries used in two APS buses. However, because flooded cells risk electrolyte leakage, they are more suitable for stationary applications like telecom repeaters, rather than vehicles. Nonetheless, vehicles were built employing the technology, ex. Chrysler TeVan, 1994; APS bus, 1997; Renault 106 and Kangoo; etc. NiCd is also not a popular choice anymore because it still has relatively low energy density among available secondary batteries, and cadmium is not environmentally friendly. Europe has recently banned their manufacture for consumer applications [European Parliament 2006].

2.2.2. Nickel metal hydride Battery

The nickel metal hydride battery (NiMH) uses nickel oxyhydroxide as its cathode and hydrogen, absorbed in a metal hydride as its anode [Larminie 2003]. It has become a popular choice for electric and hybrid vehicles because of its superior energy density, relative to lead acid and nickel cadmium batteries; and it uses more environmentally friendly metals. Second generation electric vehicles developed in the late 90's used nickel metal hydride batteries. They were seen in the GM EV1 (GEN II), Chevy S10 EV, Ford Ranger EV, Chrysler EPIC, Toyota RAV4 EV, and many others. After the EV programs were suspended around 2001 in response to a changing regulatory environment which permitted alternate solutions towards emission reduction, the NiMH battery continued to be used in virtually all hybrid electric vehicles. It could offer up to 40% higher energy density compared to NiCd but was not quite as durable and robust at the time. Additionally, it is a sealed system similar to VRLA in concept, thus "maintenance free". However, it is more sensitive to storage environment, and operating conditions. Higher temperatures and discharge rates reduce its cyclic life accordingly. NiMH also has a high self-discharge rate when compared to the nickel cadmium battery. Deep discharge cycles and elevated temperatures during operation cause a deterioration in performance. In HEV applications usable SOC variation is kept small (5% optimum, 20% maximum) to protect the batteries and to achieve approximately 300,000 shallow cycles as required for this application. Rated operating temperature is -20 to 60°C. Cell cyclic life reduces quickly at the high end of its operating temperature, easily reached through the charging cycle on electric vehicles. Storage is best at 25°C and with a partial charge state. Self-discharge rates increase with the storage temperature. The charging algorithm of a NiMH battery is more complex, as a slight voltage drop occurs at full charge accompanied by internal resistance increase. This effect needs to be monitored closely to avoid overcharge [Buchmann 2009]. It adds to the complexity of vehicle's Battery Management System (BMS).

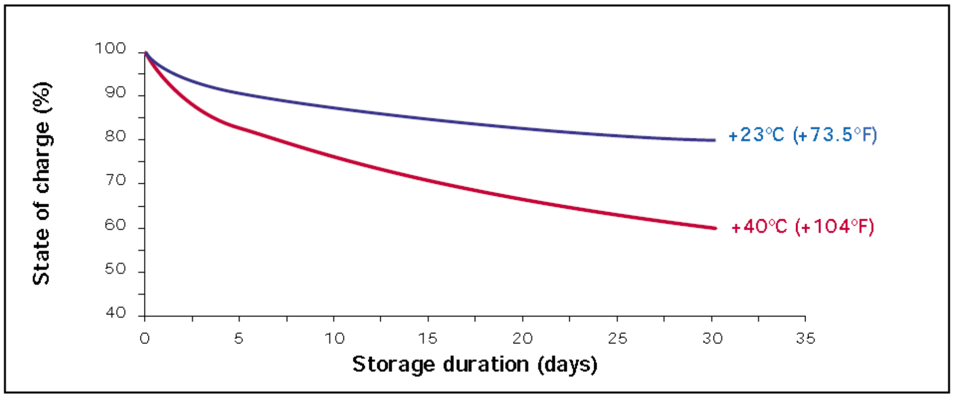

Figure 2-1, Self-discharge of NiMH as a function of temperature [SAFT 2005]

2.3. Lithium-based Battery

A large variety of lithium based batteries exists. Different chemistries of anode, cathode, and electrolyte materials give them unique characteristics in terms of cost, packaging, energy density, shelf and cyclic life.

Table 2-1, Characteristics of lithium-ion high energy batteries with different chemistries [Kalhammer 2007, Burke 2009]

Chemistry Anode/cathode	Cell voltage Max/Nom, V	Energy Density, Wh/kg	Power Density, W/kg	Cyclic life (80% DOD)	Thermal stability	Manu.
Graphite/LiNiCo MnO_2	4.2/3.7	100-190	700-1000	1000-3000	Fairly stable	Kokam, GAIA, Thunder Sky
Graphite/LiMn spinel	4.0/3.85	100-120	~1000	1000	Fairly stable	LG Chem, NEC, Samsung
Graphite/LiNiCo AlO_2	4.2/3.6	100-150	600-1000	2000-3000	Less stable	JCS, Matsushita
Graphite/Li iron phosphate	3.85/3.2	90-115	~1200	>3000	Stable	A123, Thunder Sky, HiPower, Valence
Lithium titanate/LiMn spinel	2.8/2.4	60-75	<1000	>5000	Most stable	Altairnano
Graphite/$LiCoO_2$	4.2/3.6	225	~1200	>1000	Least stable	Thunder Sky

The commercial electric vehicle segment is still in an early phase developing market where great efforts are put on selecting and testing the most suitable battery for particular vehicular applications. Due to the many powertrain packaging, life cycle costs and operating constraints faced, lithium-based batteries have recently become popular choices due to their superior combination of characteristics.

Commercially available lithium-based cells include (named after cathode material), lithium cobalt oxide, lithium manganese oxide, and mixed metal oxide batteries. A special variant was developed in the early 2000's using a polymer electrolyte, and is aptly named lithium-polymer. Generally, lithium-ion batteries have much higher energy density and higher nominal cell voltage (3.2 – 3.7 V) compared to other rechargeable batteries, while variation exists between different cathode materials. The self discharge rate is less than 1% per month compared to 20-30% a month for some early NiMH.

Originally lithium-ion batteries had short cyclic life under deep discharge, but this has been improving over the years. Similar to other types of rechargeable batteries, a capacity loss occurs under extreme operating temperature and high discharge rates. The internal resistance of lithium-ion batteries was not advantageous over other types in the beginning. Significant improvement began with the lithium polymer cell technology, and nano scale material engineering has recently also furthered this advantage. Internal resistance still increases under cycling and chronological ageing. Safety has been the biggest concern for $LiCoO_2$ and $LiMnO_2$ cathodes since they are unstable oxidation states of the metal; whereas $LiFePO_4$ is a more stable form. The material cost of cobalt was a barrier to lowering production costs of the original lithium-ion batteries. This problem is being addressed with the replacement of cobalt by aluminum, manganese, nickel oxides, and iron phosphate. Manganese cells also show good tolerance to abuse, such as high C-rate discharge. Nickel cells deliver better energy and power density. Iron phosphate is relatively inexpensive. Mixed metal oxide cells can be tailored to a balance of requirements between power, energy and safety issues.

2.4. Automotive Application

In vehicle applications, several parameters are more critical than others. The US Advanced Battery Consortium (USABC) long term commercialization goals for batteries are summarized in the Table 2-2, along with practical goals for vehicle application.

Table 2-2, Long term commercialization goal for EV according to USABC, and practical goal [Kromer 2007]

Parameters	Unit	For Electric Vehicle	Practical goal
Cycle Life	*Cycles*	1000	Deep discharge cycle provides all of the vehicle's traction energy, 60-80% DOD
Calendar life	*Years*	10	15 or sufficient for 180,000 miles of total vehicle range
Motor Power	*kW*	80	Sufficient power for acceptable dynamic performances
Useable Energy	*kWh*	40	Sufficient for >200 mile range
Specific Energy	*Wh/kg*	200	
	Wh/liter	300	
System Voltage	*V*		300-400
Power-to-Energy ratio	h^{-1}	2:1	
Mass	*Kg*	200	
Cost @ 25 K units /year	*$/kWh*	$150	

These requirements are derived from real-world vehicle operating experience. Some of the key road blocks towards commercialization of electric vehicles are battery cost, and limited range per charge. The latter can be solved by packing more batteries onboard. This leads to a further problem of reduced overall performance due to excessive mass, as the vehicle mass increases. Packaging space usually becomes the ultimate practical constraint.

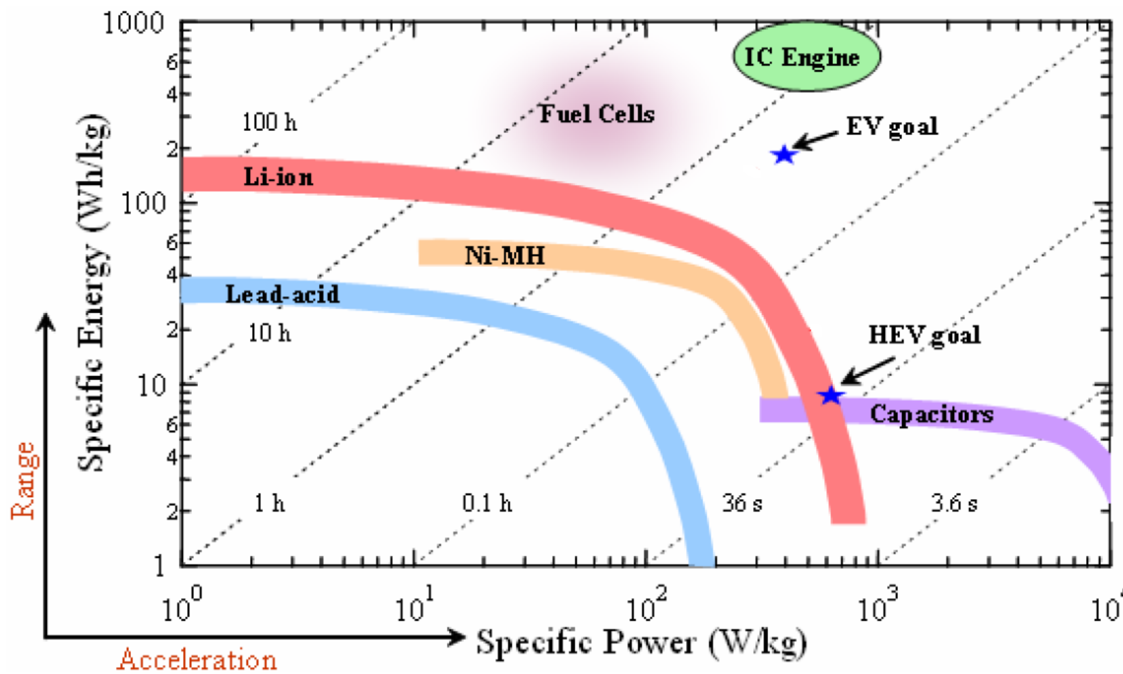

Figure 2-2, Battery energy and power vs. engine and capacitor [Srinivasan 2004]

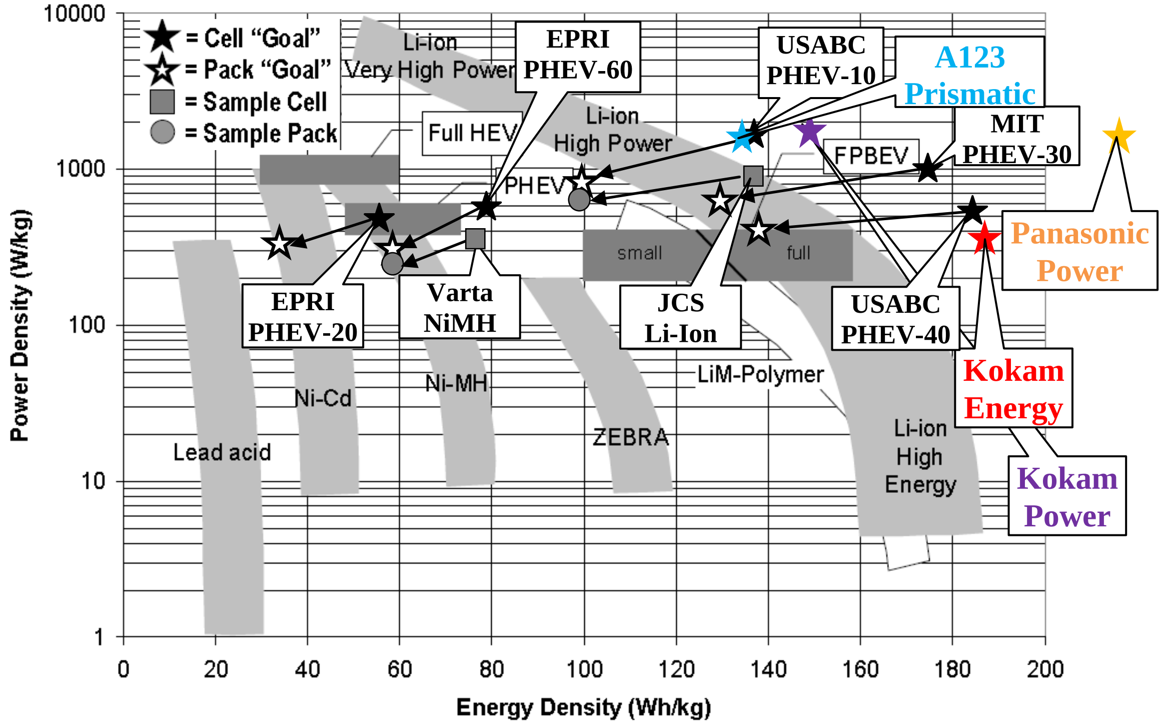

Figure 2-3, Potential of battery technology for HEV, PHEV and EV application [adpated from Kalhammer 2007]

Figure 2-2 shows the power and energy density of different battery chemistries and other energy storage technologies including IC engines and capacitors. Figure 2-3 shows the superior properties of lithium-based battery over other chemistries, and current technology status in comparison to industry goals.

Fundamentally, the electrochemical energy density of a lithium-ion battery is better than NiMH. Improvements in cell engineering, such as A123 System's nanoscale electrode coating technology delivers superior C-rate (1C = discharge current at the nominally rated Amp-hr capacity of the cell). In present HEV's NiMH batteries are well monitored and protected during operation and storage. They can last the life of the vehicle at a lower cost compared to the lithium-ion battery. As examples, Toyota's Hybrid Prius using NiMH, in taxi fleet service, are known to run well past the 300,000 km mark. RAV4 EV's at southern California Edison have tested to exceed 160,000 km without major issues. By comparison, lithium-ion is still considered a technology under experiment and development; performance shortcomings are being addressed and solved. Figure 2-4 shows the improvement of the lithium-ion battery since it first appeared in 1991. Current energy density is approximately 180-190 Wh/kg for vehicular grade EV cells, with 250 Wh/kg Li-Ni cells soon to be available [Panasonic 2009]. The performance at the power to energy density ratio requisite for hybrids or plug-in hybrids is lower, about 130-140 Wh/kg. Lithium sulfur energy cells are currently in the 350 Wh/kg range, however still under limited availability, restricted to small sizes and short cyclic life ~400 cycles [SION power 2009]. There is reason to believe these newest technologies will see further development.

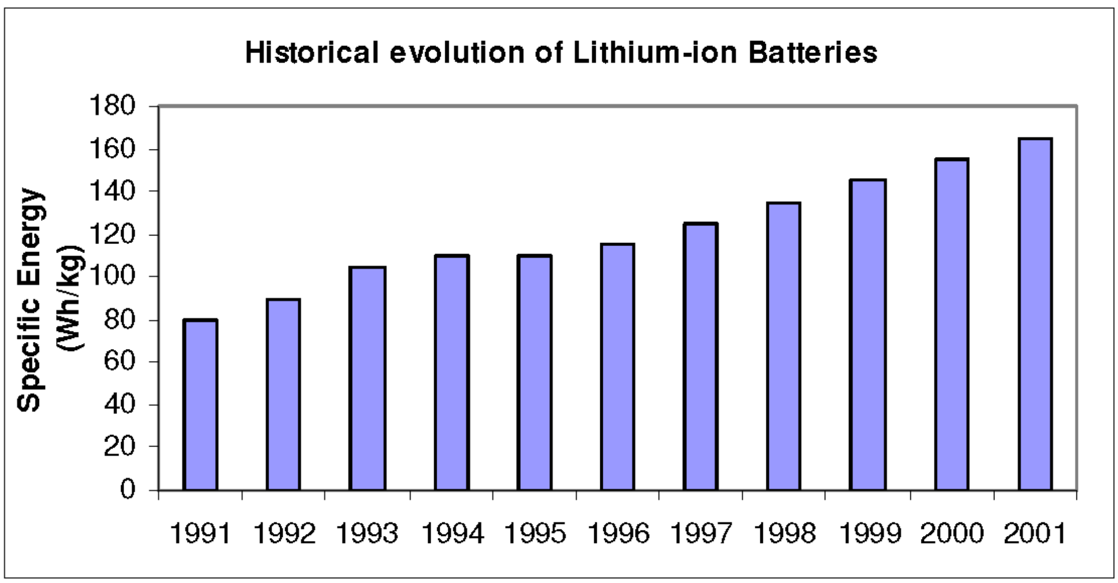

Figure 2-4, Growth of Lithium-ion battery energy density [Brodd 2005]

Battery management systems are being evolved to address the safety and durability issues. Metals now used in lithium batteries are less cost prohibitive since cobalt is no longer the predominant cathode material; as production increases, prices should drop closer to the commodity level. The influence of costs is subject of Section 7.

A lithium-ion battery diminishes in capacity with both storage and cyclic usage. Present cells only meet the minimum requirements of automotive application under ideal lab test environments. It is suggested by battery manufactures that performance is considered acceptable if the battery can maintain between 70-80% of its original capacity after deep cycling. Experiments show that many lithium-ion batteries last more than 1000 cycles under 80% DOD, some exhibit greater than 2000 deep cycles; and over 300,000 cycles can be met under shallow DOD (i.e. 5-10% DOD), a requirement for HEV and PHEV in charge sustaining operation [Pesaran 2007]. Present cells appear to meet or exceed these requirements, as shown in Figure 2-5, 2-6 and 2-7.

Table 2-3, Lithium-ion cell life cycle based on DOD [Kokam 2009]

ITEMS	Criteria	Calculated Cycle Life	Description	Remarks
DOD100%[1)]	Until 80% of Initial Discharge Capacity	> 1,400 cycles	-	Base on real test
DOD80%[2)]		> 2,500 cycles	Fitting function : y = -(0.98E-7)x2-(5.46E-3)x+100	Expected Cycle times
DOD20%[3)]		> 11,500 cycles	Fitting function : y = -(1.697E-3)x +100.07	Expected Cycle Times

1) Full Discharge 2)Partial Discharge 3)Shallow Discharge

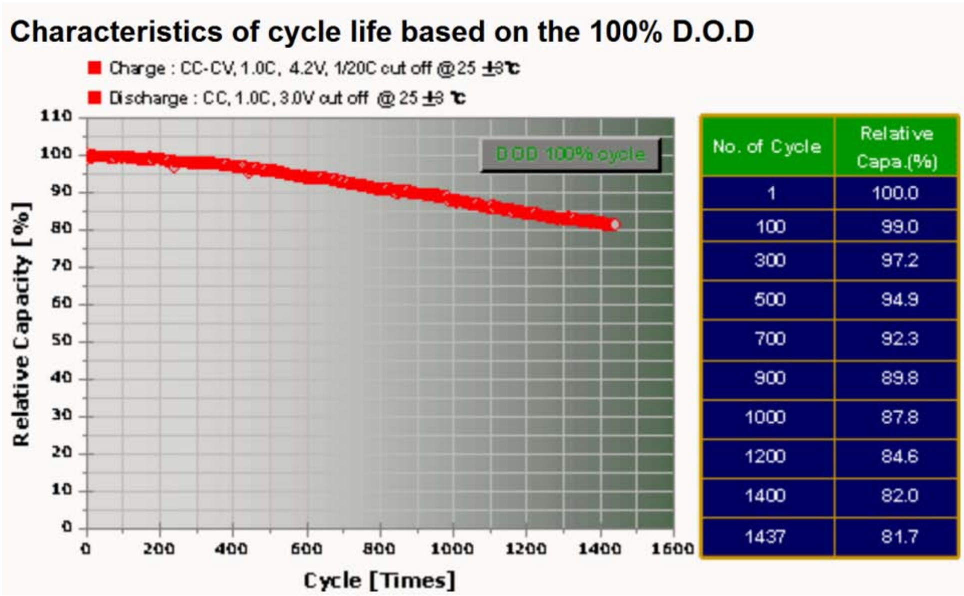

Figure 2-5, Cyclic life of Lithium-polymer cell under 100% DOD [Kokam 2008]

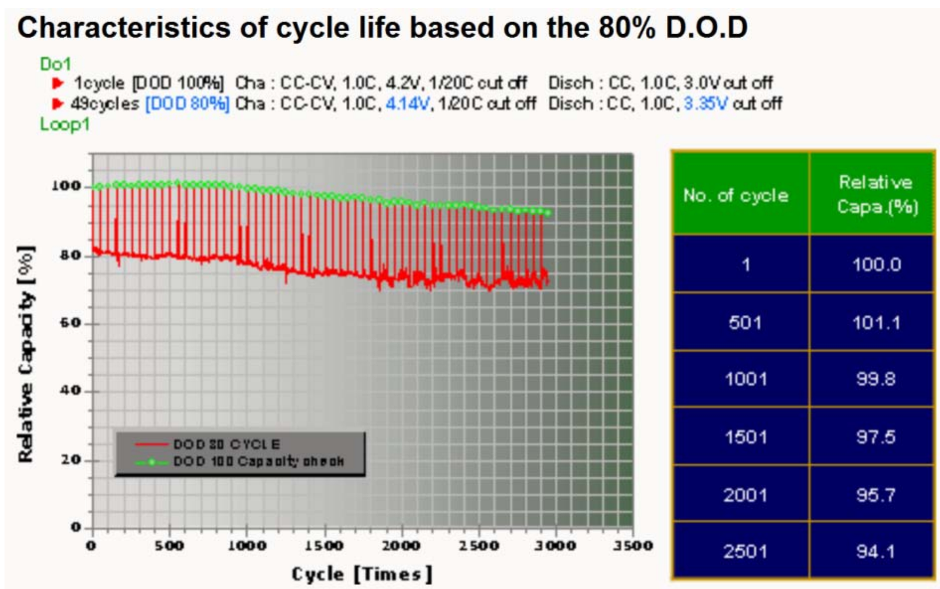

Figure 2-6, Cyclic life of Lithium-polymer cell under 80% DOD [Kokam 2008]

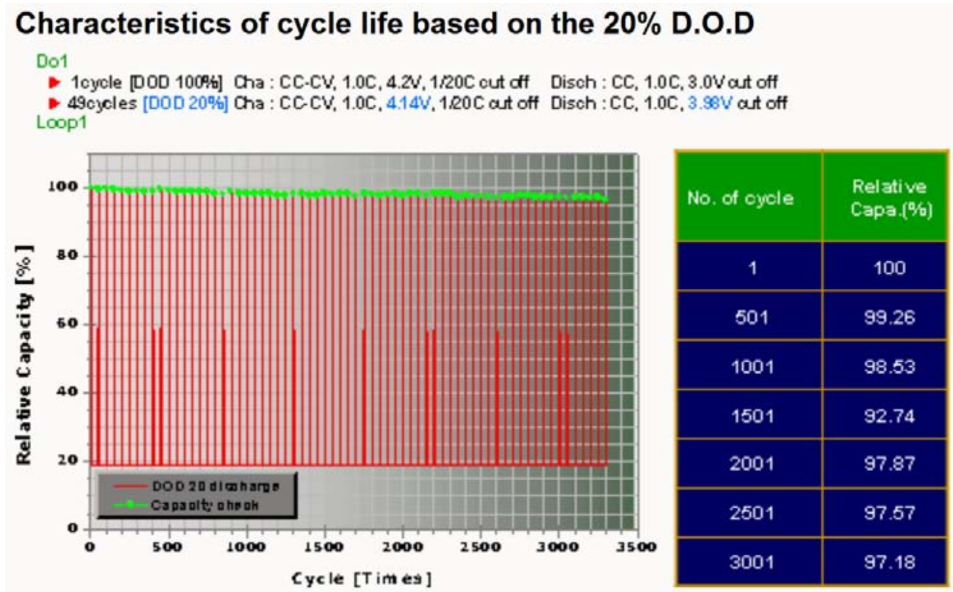

Figure 2-7, Cyclic life of Lithium-polymer cell under 20% DOD [Kokam 2008]

However, such lab generated data is under ideal operating conditions, at 25°C, often with lower discharge rate (typically 1C), less than seen in practice. In the real world, concerns are that chronological and cyclic ageing co-exist and discharge rates up to 7C may be seen for PHEV's. Life is affected by storage temperature when the vehicle is parked, raising ambient operational temperature when the vehicle is being driven. Abusive drive cycle usage and typical driving cyclic ranges (depth of discharge) need to be accounted for. Real world experiments taking all these factors into consideration have yet to be realized although they are currently being simulated in laboratories. Figure 2-8 represents temperature effects on battery life projected forward.

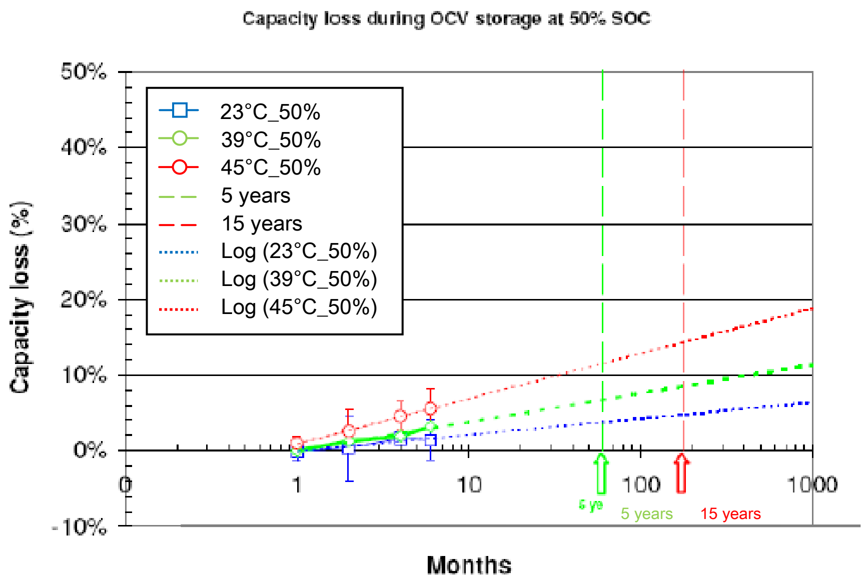

Figure 2-8, Effect of calendar life and temperature on storage capacity [Chu, 2006]

Low temperature charging causes excessive physical wear to the cell through the formation of metal dendrites penetrating insulating layers; higher temperature storage reduces calendar life from internal corrosion effects; high C rate operation, regardless of the state of charge, reduces cyclic life [Kalhammer 2007]. Calendar life limitations arise because of parasitic reactions between both electrodes and the electrolyte, particularly in the charged state, and at high temperature. These reactions lead to slow degradation of the electrodes, causing capacity and power to fade with time. Hence, calendar life degradation is largely a function of the reactivity of the electrodes with the electrolyte. Cyclic life degradation arises from permanent deposition of lithium metal on the anode, which causes both impedance growth (due to reduced surface area of the electrode) and reduced capacity (due to reduction in the quantity of active material). Research advancements have shown promising solutions towards these problems, thus it is expected that lithium-ion batteries will become dominant for automotive applications in the near future.

Currently, cost is the primary barrier for the commercialization of battery electric vehicles. The near-term USABC goal for BEV and PHEV battery prices is $200/kWh, while other organizations have targeted slightly more achievable goals. The auto industry is still far from this goal at $500-750 per kWh presently in prototype volumes, but with prices predicted soon to be below $500/kWh with production quantities in the 10,000 units per year range for vehicles like the GM Volt, Nissan Leaf, Mitsubishi i MiEV, and others entering production. In fact, battery suppliers' bids are already in the mid-$400/kWh range on battery packs for 2011/2012. However, this is believed to be influenced by battery makers' desire to lock-up high volume contracts at the cost of profitability. For battery makers to achieve the mid-20% gross margin target, their cost is expected to drop to $375-$400/kWh in 2015 [Deutsche Bank 2010].

Table 2-4, OEM battery cost projections [Kromer 2007]

Source	Cost ($/kWh)
USABC	$200
Battery Technology Advisory Panel	$270
Argonne National Laboratory	$225

The USABC projections are made on the basis of an OEM production levels, which constitutes more than 100,000 vehicles per year. Currently, the lowest retail price for production prototype quantities (≈ 1*10^6 Ah) of lithium metal-oxide cells is at $265 per kWh ($LiFePO_4$, manufactured in China) and $700 per kWh for large format lithium polymer cells (Kokam). The actual battery cost is higher as it includes cell stack assembly, control electronics, cooling systems and packaging. Presumably as Auto OEM's are forming joint ventures with battery companies, production level costs will approach the current "China price" for consumer level cells, presently at $275 /kWh.

Advances in battery chemistry should enable further cost reduction by way of increased energy density from a given quantity of material. Table 2-5 provides a summary of key battery chemistry capabilities and cell costs at retail.

Table 2-5, Summary of battery chemistry and characteristics

Battery type	Energy density, Wh/kg	Power density, W/kg	Capital Cost, $/kWh	Cyclic life, @80% DOD
Lead acid [Optima yellow top]	25-25	200-400	120-150	400-600
Nickel metal hydride [Cobasys, Saft]	60-70	150-300	150-200	800-1500
Nickel cadmium [Saft]	50-55	150-350	200-400	800-2000
Lithium-ion				
LiMn [Thundersky]	100-1709	~1000	305-416	500-1000
$LiCoO_2$ [Thundersky]	225	~1200	305-416	1000-2000
$LiFePO_4$ [HiPower]	90-115	~1000	366	1000-3000
$LiFePO_4$ [A123] (nano-coating)	135	1354	~550	1000-2000
LiS [Sion Power]	350-450	>2000	potentially low	300-400
LiNCM [Kokam]	135-190	600-1200	1000	>2000

2.5. Battery Safety

It is widely accepted across the industry that the lithium-ion family of batteries show promising results in vehicular application. Energy cells are available exceeding 200 Wh/kg with good tolerance to high discharge (C-rate), and continue to improve. Remaining technology concerns regard the safety and life of lithium-ion batteries under stress (high temperature and C-rate). National Renewable Energy Laboratory (NREL) has performed battery thermal analysis and characterization, simulation and requirements analysis, addressing issues related to battery thermal control and improving the thermal performance of energy storage systems. For example, tests have been performed on different chemistries of lithium based batteries, including the iron phosphate cells from

A123, lithium polymer cells from LG Chem, and Nickel-Cobalt-Aluminum oxide cells (NCA) from Johnson Controls. Taking the iron phosphate cell through a 1C discharge cycle at temperatures of 30°C, 0°C, -15°C and -30°C, the resulting thermal efficiency was 97.8%, 90.1%, 79.0% and 47.6% respectively. The thermal efficiency of $LiFePO_4$ cells remain above 92% during a 1C charging cycle, under all four testing temperatures. Other data show that energy efficiency of the battery for different driving cycles is varied, the more aggressive driving cycle (US06) results in less efficient (90.1% as compared to 94.5% for milder driving); and the SOC window of 75 to 50% is most efficient, while deep discharged cells (25% to 0% SOC window) are least efficient. Under a 70 A continuous discharge test, the positive end of the cylindrical cell appears to be 3.5°C hotter than the other end, and surfaces neighboring other cells are 2°C hotter than the front of the cell exposed to natural convective cooling. Overall, such cells don't exhibit significant areas of thermal concern [Howell 2009].

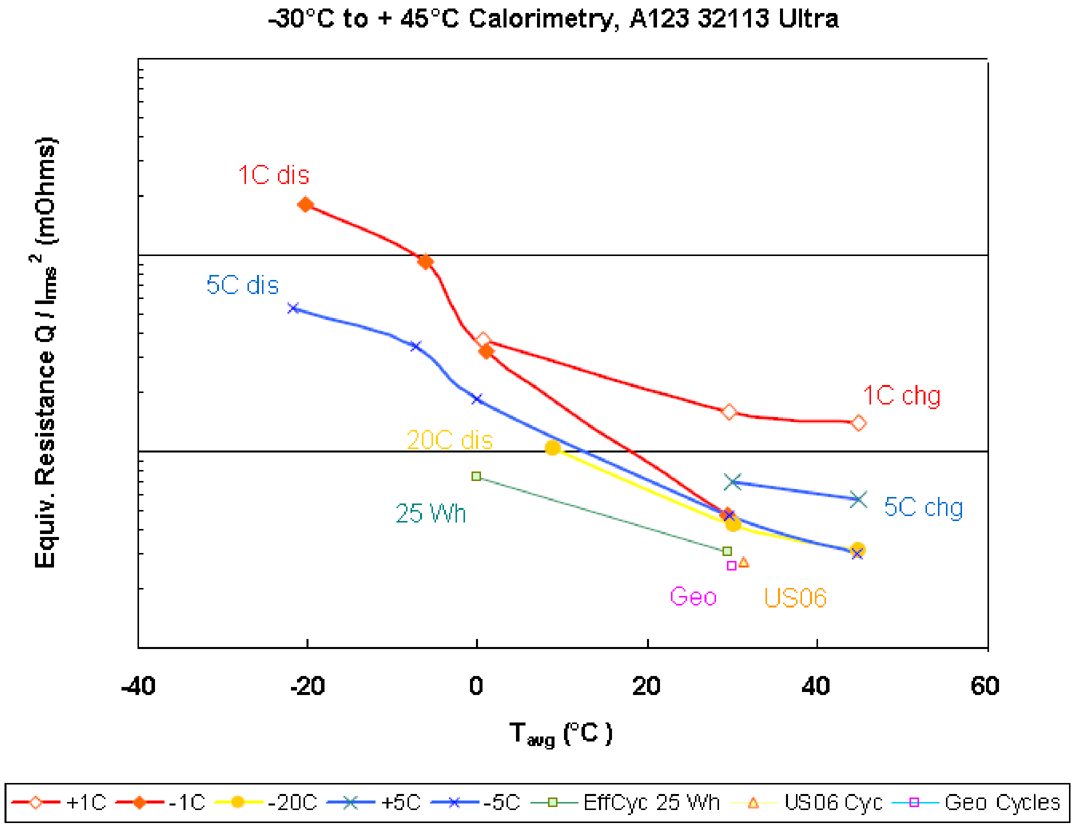

Figure 2-9, Heat generation resistance for various charge/discharge cycles and temperature, Iron Phosphate [Howell 2009]

In similar experiments, polymer cells were taken through a 5C constant current discharge cycles, and showed the same trends in thermal efficiency variation with temperature change, and energy efficiency variation with driving pattern. The maximum temperature rise during the discharge cycle is approximately 5°C, therefore no significant thermal stress was seen [Howell 2009].

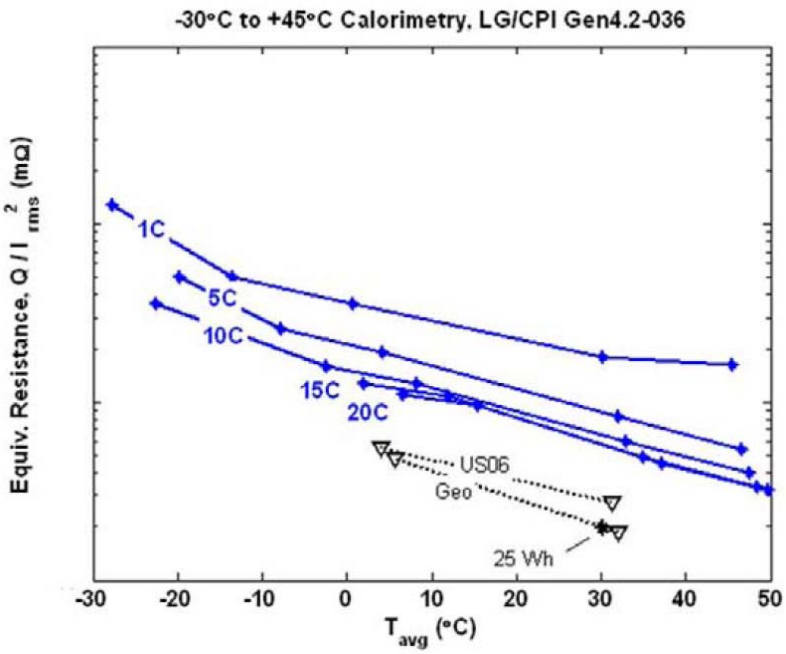

Figure 2-10 Heat generation resistance for various charge/discharge cycles and temperature, Li-poly [Howell 2009]

Detailed test results of the NCA cells were not released, however it is still apparent from Figure 2-11 that thermal efficiency is better at the high end of the test temperature where less heat is generated.

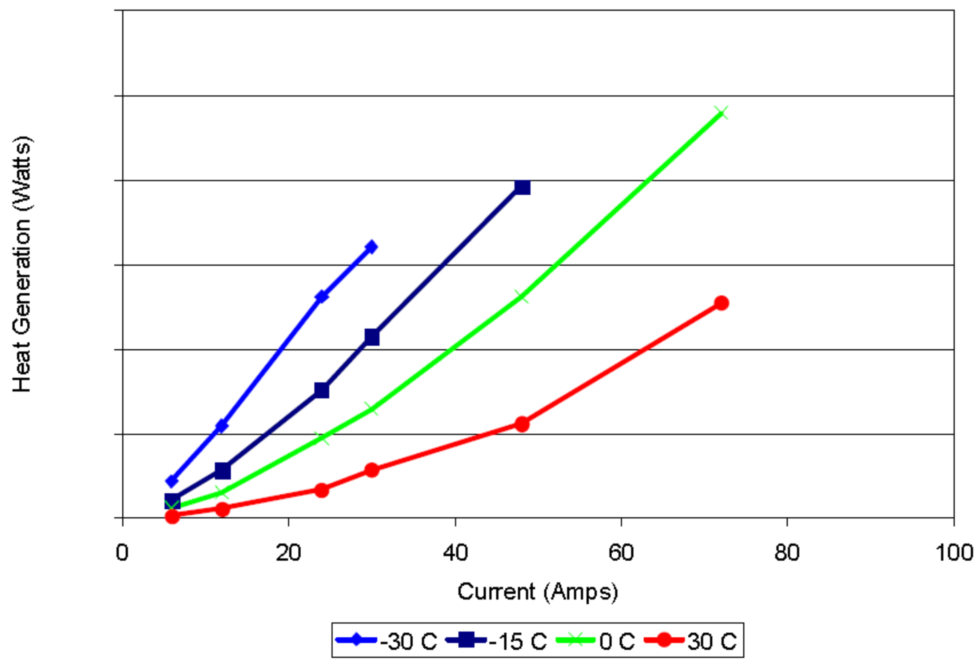

Figure 2-11 Heat generation under various temperature, NCA [Howell 2009]

In summary, independent lab tests at various research institutes on the latest cell chemistries have shown normal temperature rise, and no immediate thermal concern for these lithium-ion batteries, even under aggressive driving patterns.

2.6. Conclusion

Battery development is constrained around tradeoffs among five main parameters: power, energy, longevity, safety and cost. Increasing power density requires higher voltages or alternate chemistries that often reduce longevity, safety, or increase costs. Higher energy density tends to reduced power density. Increasing all of power, energy, and longevity adds to cost, and spurs next generation chemistries such as lithium sulfur (>350 Wh/kg, limited to about 400 cycles presently). Considering the long term projections around vehicle requirements and battery system development, given proper cell management systems the lithium-based battery is far superior to the nickel metal hydride chemistry it replaces. Early safety concerns were specific mainly to the Lithium Cobalt oxide chemistry, while more recent variants have shown good behavior and greatly reduced concern for thermal run-away. With recent technology advancements, electric vehicles could begin taking a share of the market over the next decade. In order to predict what should be achievable presently and in the near term, the simulation tool Powertrain System Analysis Toolkit (PSAT) was used to estimate vehicle performance, details are given in Section 3.

3. Analysis Methodology

PSAT is a modeling and simulation software developed on Matlab/Simulink at Argonne National Laboratory since the mid 90's. It contains more than 180 configurations of vehicle powertrains, including conventional, hybrid and electric; and standard drive schedules used by the EPA and equivalent agencies from Japan and Europe. The software is capable of running a virtual vehicle with a user-defined architecture through drive cycles and evaluates the energy usage at the component, drivetrain and vehicle levels, as well as estimating emission levels.

Organization of component blocks in Simulink is based on the Bond Graph, a graphical representation showing the energy flow of dynamic systems, as depicted in Figure 3-1.

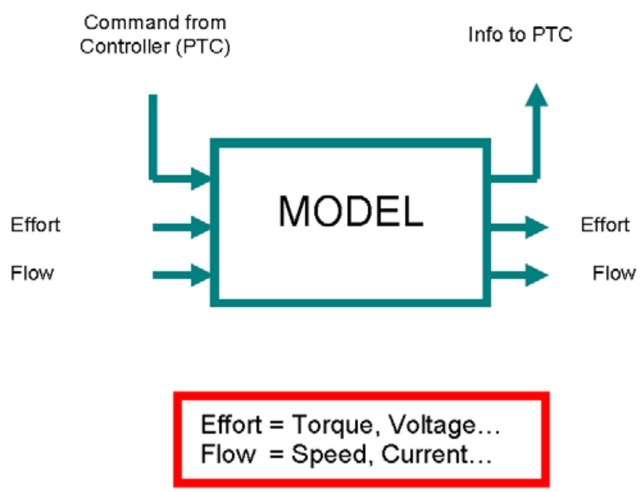

Figure 3-1, I/O of PSAT component models using a Bond Graph [Rousseau 2001]

The first ports are used for information. Inputs are the component commands (i.e., on/off engine, gear number, etc.). Outputs, also known as "sensors values", are simulated measures (i.e., torque, rotational speed, current, voltage, etc.). The second ports carry the effort (i.e., voltage, torque), and the last ports the flow (i.e., current, speed).

In the case where one component needs to be used more than once in a drivetrain configuration, for example a hybrid electric drivetrain with more than one electric motor, different component models are masked to allow reusing of the same model. PSAT uses common nomenclature for variable names of component models, both at the component level (Simulink blocks) and at a software level (Matlab initialization files).

Powertrain controllers also have a generic structure common to all configurations. Taking the accelerator pedal as an example, after evaluating information coming from the component models, constraints of the system (torque output) can be established. These limits are then taken into account to define the optimized control strategy to minimize fuel consumption and emissions. Finally, the transient states are taken into account by defining the actions necessary to satisfy the control strategy demands. If the control strategy decided to shift gears with a manual transmission, the system must disengage the clutch, engage neutral gear, engage the new gear, and engage the clutch again. Since a complete PSAT model of a vehicle is built in stages, once drivetrain components are selected, the next stage is to select powertrain controllers. These can be interchanged to test the impacts of different control strategies on performance.

The front end of PSAT is a Graphical User Interface that allows users to exchange drivetrain components and component initialization files. Users can modify existing models at any level, or create their own models by scaling existing data. In order to assess the influence of different parameters on consumption or drivability, a parametric study is also available. In the case of an energy consumption test for a hybrid configuration, a state-of-charge (SOC) equalization algorithm is available so that the consumption results from different configurations or strategies can be compared with the same SOC.

After the user builds the drive configuration, selects the powertrain controller and drive cycles, the model will run and results are saved and presented in the GUI. Simulation results are saved in different folders named after drive cycles with initial condition variables of simulation along with a file to rerun the same test.

Figure 3-2 shows a sample simulation of a hybrid electric vehicle performed in PSAT. More details are available in Appendix D.

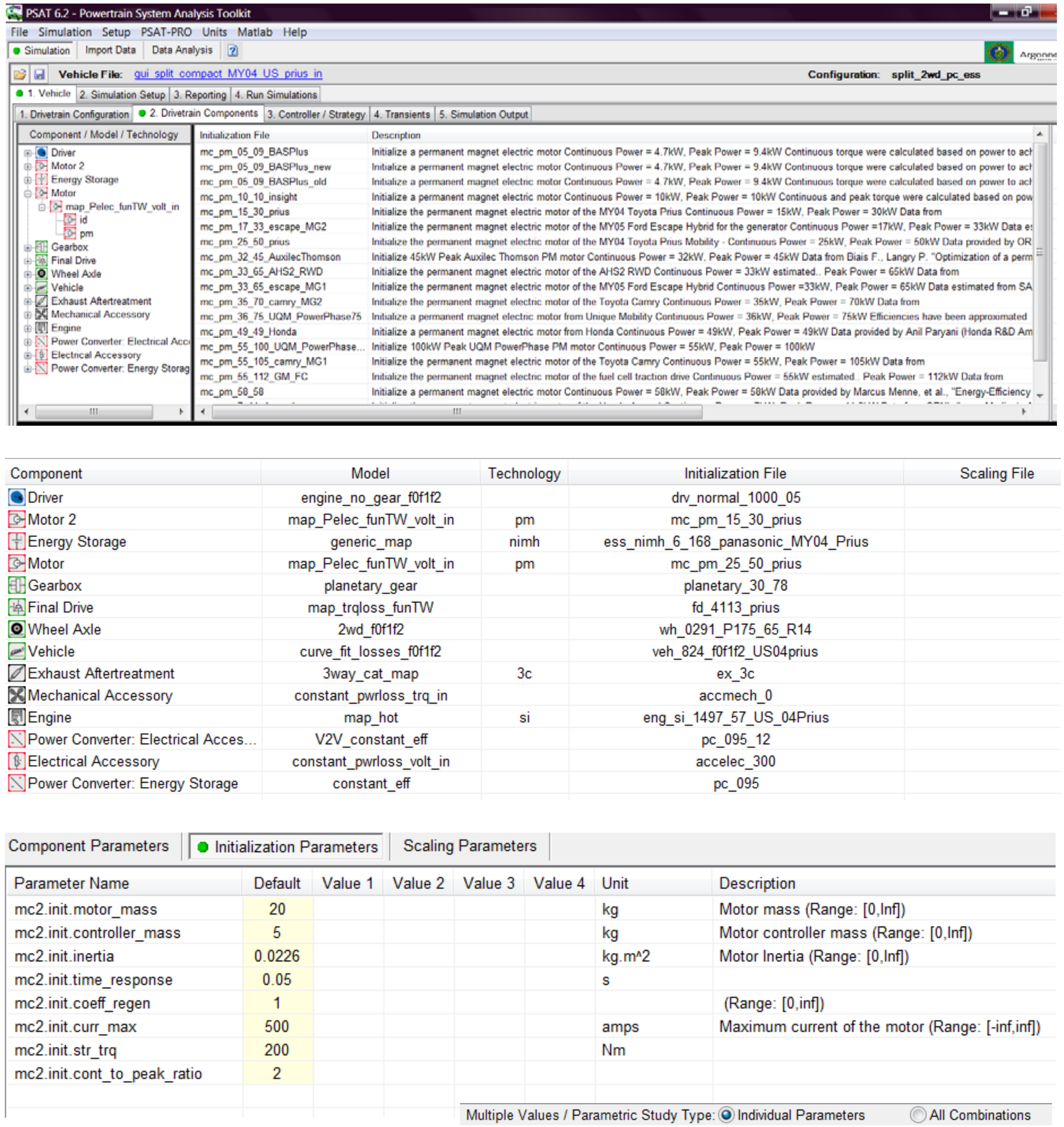

Figure 3-2, GUI layout, from the top: Component library, Component selection, Component parameters

Users first need to select a drivetrain configuration to be simulated, i.e. conventional, hybrid (parallel, series, parallel-series), or full electric; then drivetrain components are chosen from the library. After selecting, details of the components are displayed and changes to the model at the component level and to the initialization files can be made.

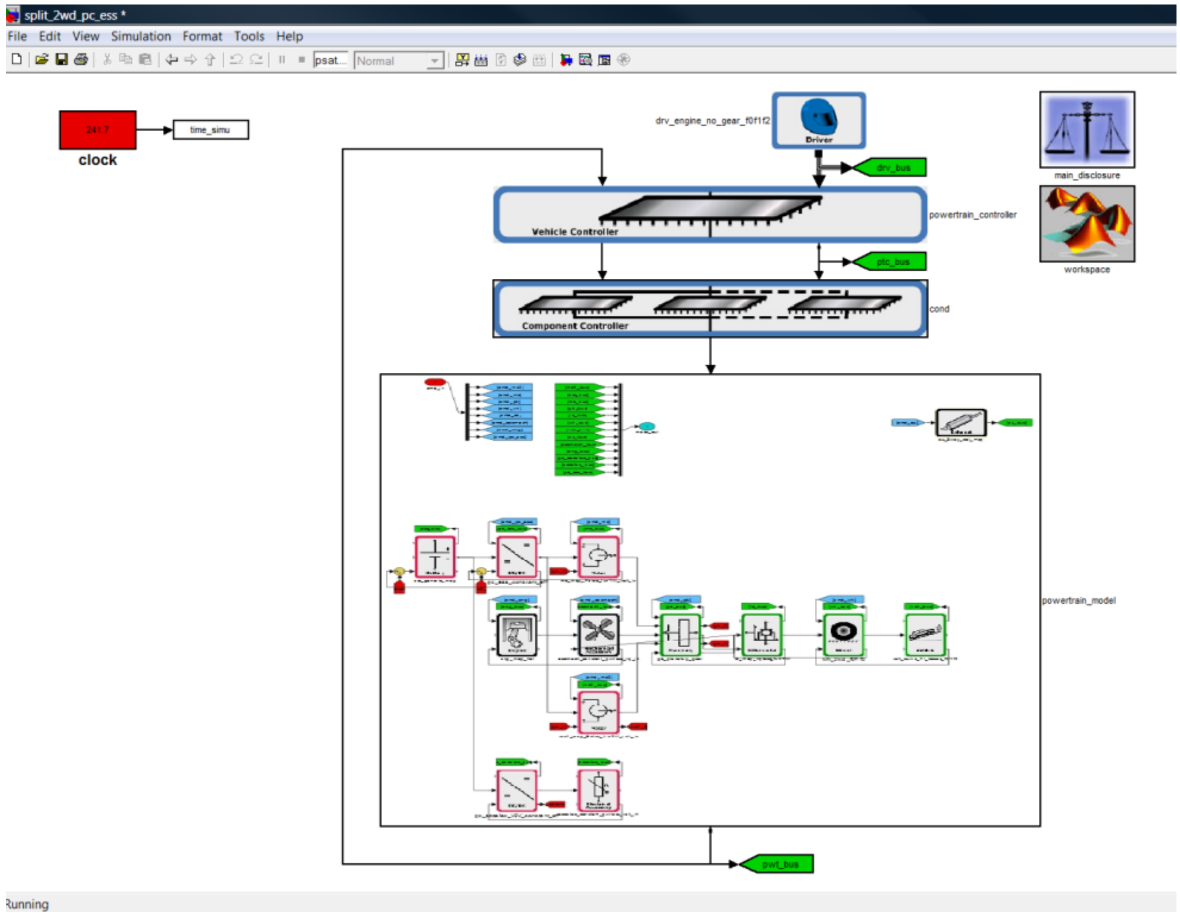

Figure 3-3, Drivertrain structure

The software automatically compiles all parts of the simulation. A timer at the top-left corner indicates the progress of a simulation.

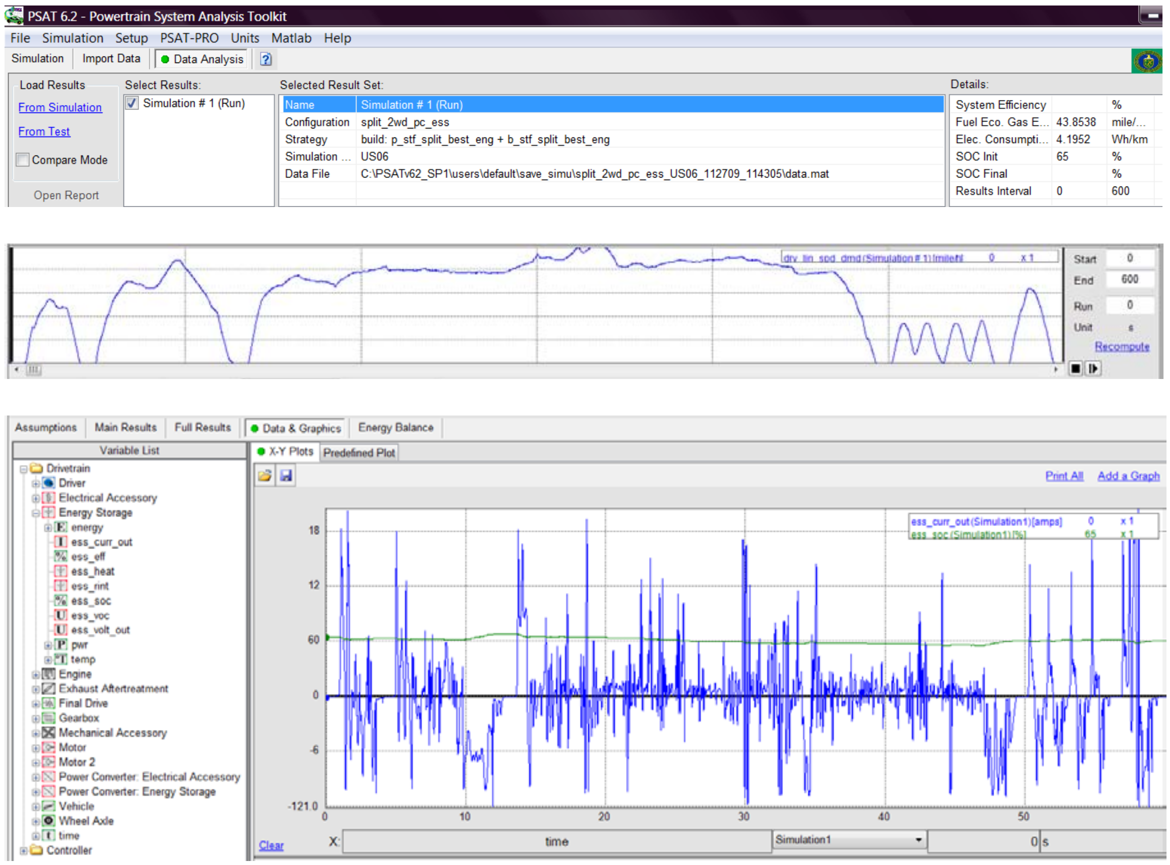

Figure 3-4, Data analysis, from the top: simulation summary, drive cycle speed demand, detail result

The GUI allows faster post-processing analysis by presenting results graphically, where simulation data can be analyzed individually or overlaid.

3.1. Vehicle road test

Prior to vehicle instrumentation, a simulation was performed using PSAT to validate the powertrain model of the S-10 EV against EVAmerica road test results for an identical 1997 lead acid battery powered truck, as presented in Appendix A. Results on modeling the EVAmerica J1634 drive cycle gave correlation on energy consumption within 0.3% of the road test results recorded at the time. This provided assurance that the simulation model was sufficiently tuned.

At the UOIT Electric and Hybrid Vehicle Lab, a Chevy S-10 EV was fitted as a rolling dynamometer (by the author) to collect data from road tests. Torque on the half shafts was measured using a pair of 350 ohm strain gauges in a half-bridge configuration. Data from the strain gauges was transferred to a laptop wirelessly and recorded in real-time, shown in Figure 3-5. Two Microstrain SG-Link-1CH 900 MHz transceivers were used in a recording mode. These data files were downloaded to a laptop at the end of the test. Vehicle speed, instantaneous battery voltage and current draw were pulled from the vehicle's onboard Diagnostics Link using a custom built ALDL 8192 baud interface circuit. Since the electric truck used for road tests was equipped with an aged lead acid battery, and a new battery of such format has been unavailable since the end of the EV program, a mild urban drive cycle (top speed 63 km/h, average speed 33 km/h) was developed to avoid over-stressing the batteries. The primary purpose of these tests was to verify and calibrate PSAT modeling parameters and access actual values of "to-the-road" energy conversion efficiency in order to better simulate and understand real world performance. In conjunction with available motor/inverter efficiency maps, this data is employed to tune models.

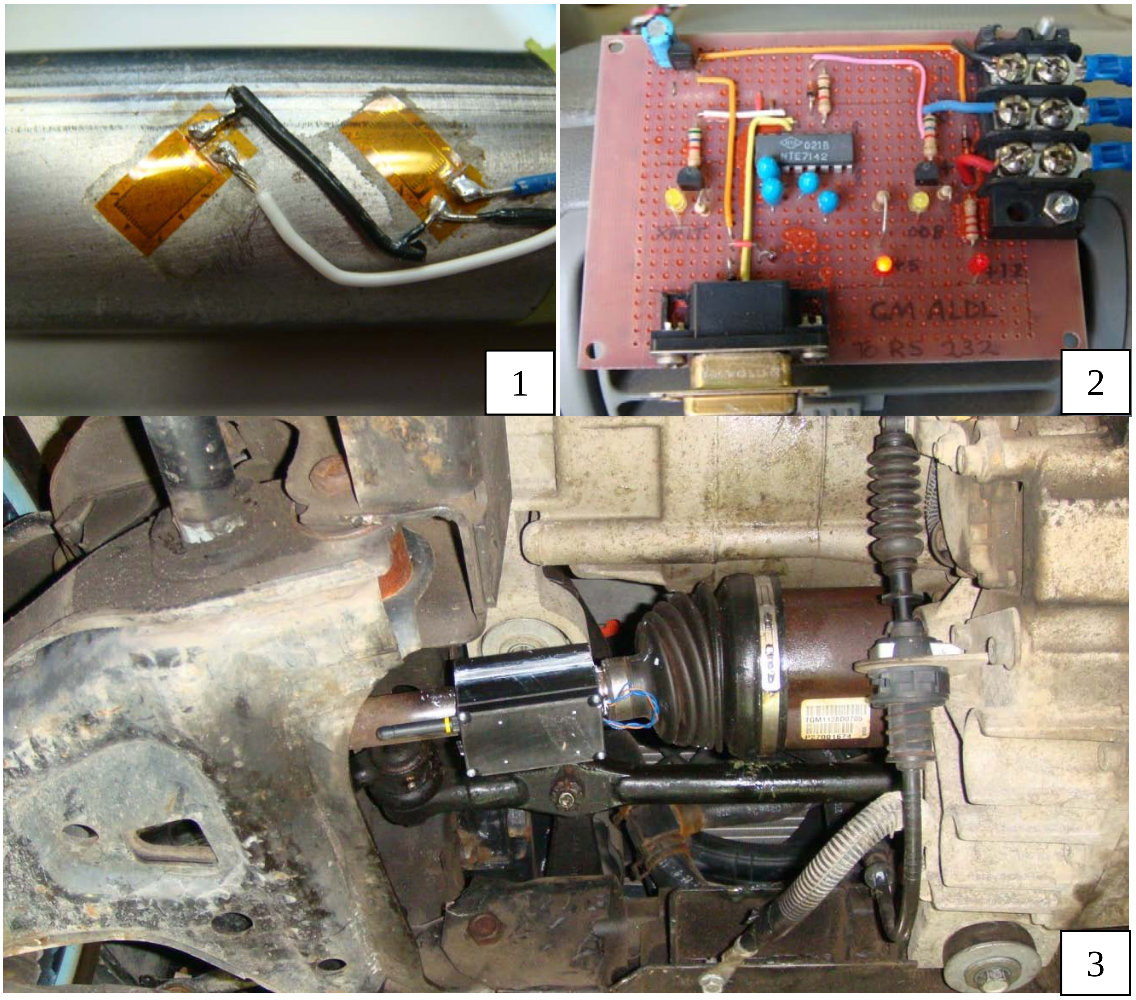

Figure 3-5, SG-Link 900Mhz wireless strain gauge transceiver (1, 3) and ALDL 8192 baud interface board (2)

Calibration of the strain gauge was done by applying torque to the half shaft by hanging weights from the outer diameter of the wheel. Calibration weights were increased in increments of approximately 30 kg, from 0 to the maximum of 380 kg; and the length of the moment arm was 0.47 m (0 to 1752 Nm). The maximum output torque of the motor is 180 Nm with a single speed reduction ratio of 10.946, 1970 Nm at the wheels.

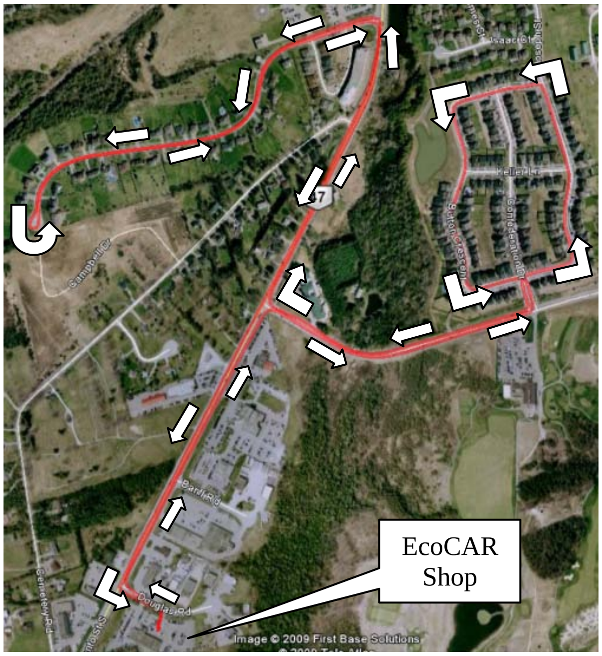

Figure 3-6, Satellite image of the test drive

The closed loop test drive was done in a typical residential neighborhood on dry asphalt surfaced roads. Twenty test drives were run on the same route to ensure the consistency of the data collected. Figure 3-6 shows a satellite image of the drive route. Figure 3-7 depicts the speed profile used for the following analysis.

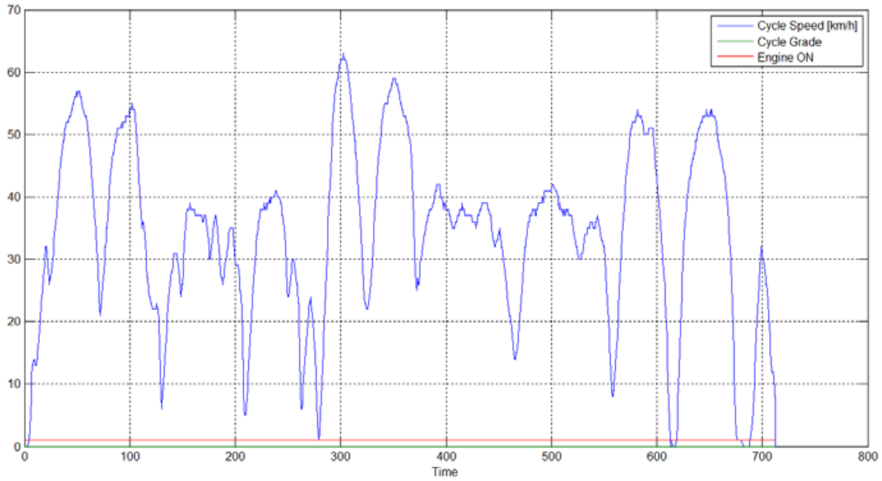

Figure 3-7, Road test drive speed profile

The typical internal resistance of a brand new Panasonic EV1260 lead acid cell is 2.2 mΩ according to manufacturer's data. Aged lead acid batteries suffer from sulfation [Ruetschi 2004]. They lose the ability to hold charge, especially if they are left in a discharged state too long, which was the case for this electric pickup truck. Even the best cells in the pack are only capable of holding half of the rated capacity, which translates to less than half of the original range due to increases in internal resistance. However, batteries in the pack are not “aged” equally, resulting in differences in the state of health of each battery module. The truck’s energy consumption during the road test turns out to be higher than the simulated truck, however recording through-put efficiency of the powertrain during the road tests was the primary objective. Road test and simulation results are summarized in the Table 3-1. For both cases, only the forward direction (tractive) energy flow was examined.

Table 3-1, S10 Road Test Results

	S10 Road Test	**PSAT Simulation**
Average Traction Power, kW	10.6	7.9
Average Traction Efficiency, %	40%	69%
Average Speed, km/h	13.7	13.7
Energy Consumption, Wh/km	327.2	182.1

Readings taken by the ALDL board were in fact the voltage and current drawn at the DC bus, which highlights the effect of a poor power factor at low speed and load. For this particular motor / inverter combination, the power factor is as low as 0.12 when the load is small.

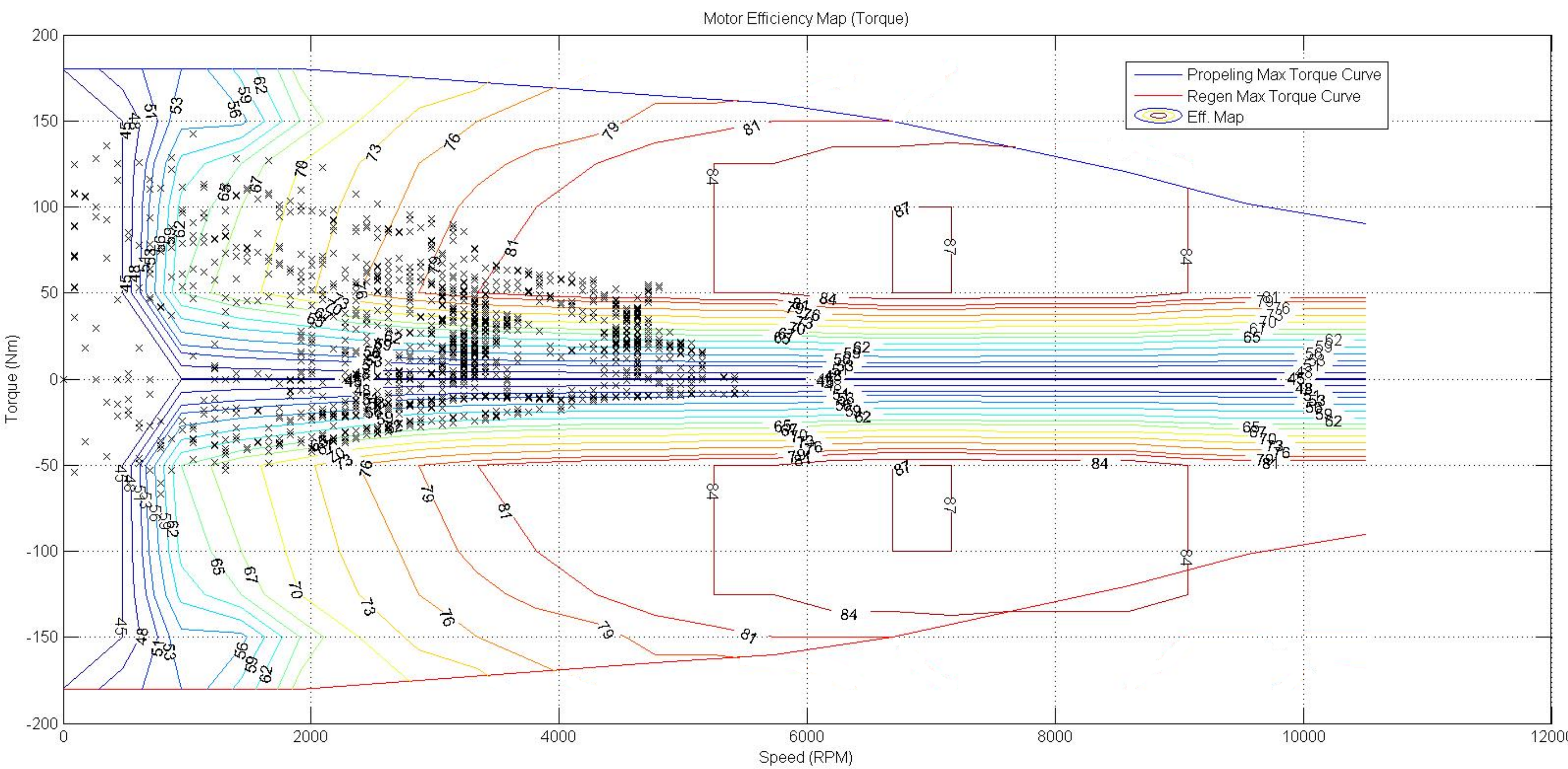

Figure 3-8, S10 motor / inverter efficiency map overlaid on drive cycle profile

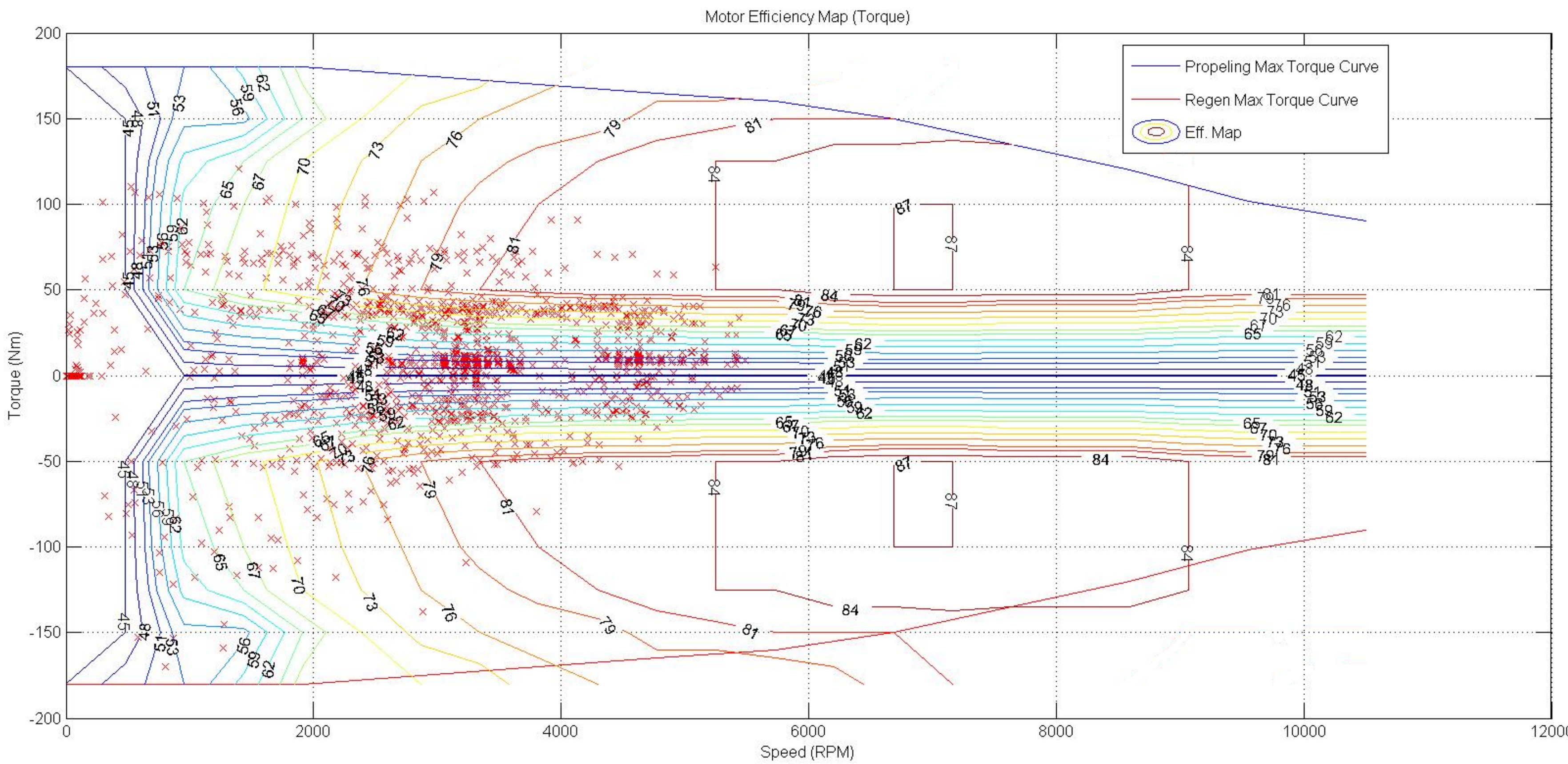

Figure 3-9, PSAT simulated drive cycle profile overlaid on motor efficiency map

Operating points from the road test is plotted on the motor efficiency map, Figure 3-8. The truck was taken through the residential neighborhood drive cycle, where operation was concentrated at the low speed and low efficiency regions. This is reflected in the acutal energy consumption over the drive cycle, 327 Wh/km. The PSAT simulation using parameters of typical new lead acid batteries is shown in Figure 3-9 by comparison. PSAT generates 10 data points per second while ALDL transmits at most 2 readings per second. Therefore, PSAT data was condensed in the above plot to make it more representative when compared with the road test data. As shown, over the PSAT simulation, the truck exhibits a better overall efficiency, but the motor is still operating in its relative inefficient zone. This typical drive around a residential neighborhood highlights how even electric machines thought to be very efficient are actually running at poor efficiency (<50%) in many situations.

	A	B	C	E	F	G	I	J
1	Node 76			Node 20				
2								
3	Time (ms)	Channel 1	**Torque**	Time (ms)	Channel 1	**Torque**	**Time_adjusted**	**Torque Tot_adjusted**
4	0	1031	-296.736	0	1218	-256.89	-6.5	-589.6258
5	0.03125	2071	15.0558	0.03125	2036	27.6108	-6.46875	6.6666
6	0.0625	2072	15.3556	0.0625	2035	27.263	-6.4375	6.6186
7	0.09375	2071	15.0558	0.09375	2035	27.263	-6.40625	6.3188
8	0.125	2070	14.756	0.125	2035	27.263	-6.375	6.019
9	0.15625	2070	14.756	0.15625	2033	26.5674	-6.34375	5.3234
10	0.1875	2069	14.4562	0.1875	2033	26.5674	-6.3125	5.0236
11	0.21875	2069	14.4562	0.21875	2034	26.9152	-6.28125	5.3714
12	0.25	2068	14.1564	0.25	2031	25.8718	-6.25	4.0282
13	0.28125	2068	14.1564	0.28125	2032	26.2196	-6.21875	4.376
14	0.3125	2068	14.1564	0.3125	2031	25.8718	-6.1875	4.0282
15	0.34375	2067	13.8566	0.34375	2033	26.5674	-6.15625	4.424
16	0.375	2067	13.8566	0.375	2031	25.8718	-6.125	3.7284
17	0.40625	2068	14.1564	0.40625	2031	25.8718	-6.09375	4.0282
18	0.4375	2067	13.8566	0.4375	2031	25.8718	-6.0625	3.7284
19	0.46875	2066	13.5568	0.46875	2031	25.8718	-6.03125	3.4286
20	0.5	2066	13.5568	0.5	2031	25.8718	-6	3.4286
21	0.53125	2066	13.5568	0.53125	2031	25.8718	-5.96875	3.4286
22	0.5625	2067	13.8566	0.5625	2031	25.8718	-5.9375	3.7284
23	0.59375	2066	13.5568	0.59375	2030	25.524	-5.90625	3.0808
24	0.625	2065	13.257	0.625	2030	25.524	-5.875	2.781
25	0.65625	2066	13.5568	0.65625	2029	25.1762	-5.84375	2.733
26	0.6875	2064	12.9572	0.6875	2029	25.1762	-5.8125	2.1334
27	0.71875	2064	12.9572	0.71875	2030	25.524	-5.78125	2.4812
28	0.75	2065	13.257	0.75	2029	25.1762	-5.75	2.4332
29	0.78125	2065	13.257	0.78125	2029	25.1762	-5.71875	2.4332

Figure 3-10, Sample data collected from strain gauge, 30 Hz sampling rate

	A	B	C	D	E	F	G	H	I	J	K	L	M
3	time	time	odometer	volts	amps	pamps	soc	speed	**speed**	**Power_batt**	**Wheel Speed, rad/s**	**Motor Speed, rad/s**	**Motor Speed, RPM**
4	msec/10	sec	Km*10	/2	*2	*2	%	kph	**m/s**	**Watt**			
5	3897843	0	0	163	-4	-8	95	0	0	-652	0	0	0
6	3898010	1.67	0	163	-3	-6	95	0	0	-489	0	0	0
7	3898142	2.99	0	163	-4	-8	95	0	0	-652	0	0	0
8	3898227	3.84	0	163	-4	-8	95	1	0.277777778	-652	0.835425534	9.144567893	87.32419095
9	3898238	3.95	0	163	-3	-6	95	1	0.277777778	-489	0.835425534	9.144567893	87.32419095
10	3898298	4.55	0	163	-5	-10	95	1	0.277777778	-815	0.835425534	9.144567893	87.32419095
11	3898353	5.1	0	163	-5	-10	95	3	0.833333333	-815	2.506276601	27.43370368	261.9725729
12	3898358	5.15	0	161	-17	-34	95	3	0.833333333	-2737	2.506276601	27.43370368	261.9725729
13	3898418	5.75	0	160	-33	-66	95	5	1.388888889	-5280	4.177127669	45.72283946	436.6209548
14	3898478	6.35	0	158	-51	-104	95	8	2.222222222	-8058	6.68340427	73.15654314	698.5935276
15	3898538	6.95	0	157	-62	-127	95	11	3.055555556	-9734	9.189680872	100.5902468	960.5661005
16	3898598	7.55	0	157	-60	-123	95	13	3.611111111	-9420	10.86053194	118.8793826	1135.214482
17	3898658	8.15	0	157	-47	-95	95	13	3.611111111	-7379	10.86053194	118.8793826	1135.214482
18	3898712	8.69	0	157	-47	-95	95	14	3.888888889	-7379	11.69595747	128.0239505	1222.538673
19	3898718	8.75	0	161	-5	-10	95	14	3.888888889	-805	11.69595747	128.0239505	1222.538673
20	3898778	9.35	0	162	9	9	95	14	3.888888889	1458	11.69595747	128.0239505	1222.538673
21	3898888	10.45	0	162	9	9	95	13	3.611111111	1458	10.86053194	118.8793826	1135.214482
22	3898922	10.79	0	163	15	15	95	13	3.611111111	2445	10.86053194	118.8793826	1135.214482
23	3898982	11.39	0	164	13	13	95	13	3.611111111	2132	10.86053194	118.8793826	1135.214482
24	3899037	11.94	0	164	13	13	95	14	3.888888889	2132	11.69595747	128.0239505	1222.538673
25	3899042	11.99	0	162	-5	-10	95	14	3.888888889	-810	11.69595747	128.0239505	1222.538673
26	3899102	12.59	0	159	-41	-83	95	15	4.166666667	-6519	12.53138301	137.1685184	1309.862864
27	3899162	13.19	0	157	-54	-110	95	16	4.444444444	-8478	13.36680854	146.3130863	1397.187055
28	3899222	13.79	0	156	-68	-139	95	17	4.722222222	-10608	14.20223407	155.4576542	1484.511246
29	3899278	14.35	0	156	-68	-139	95	19	5.277777778	-10608	15.87308514	173.74679	1659.159628
30	3899282	14.39	0	154	-80	-166	95	19	5.277777778	-12320	15.87308514	173.74679	1659.159628
31	3899342	14.99	0	153	-91	-190	95	20	5.555555556	-13923	16.70851068	182.8913579	1746.483819

Figure 3-11, Sample data collected from the vehicle's ALDL network, asynchronous sampling times

Sample data collected from the strain gauge and the ALDL network is shown in Figure 3-10 and 3-11. The timestamps of the strain gauge data are manually adjusted to best match the ALDL data because the two are not logged at exactly the same time or rate. The strain gauge logs at a rate of 30 Hz. ALDL networks supply readings at an asynchronous speed, twice a second at most and no new readings generated when energy consumption (current drawn) stays unchanged. This difference causes some inconsistency in the results requiring manual adjustments and filtering but was still able to sufficiently represent the truck's operating status throughout the test drive.

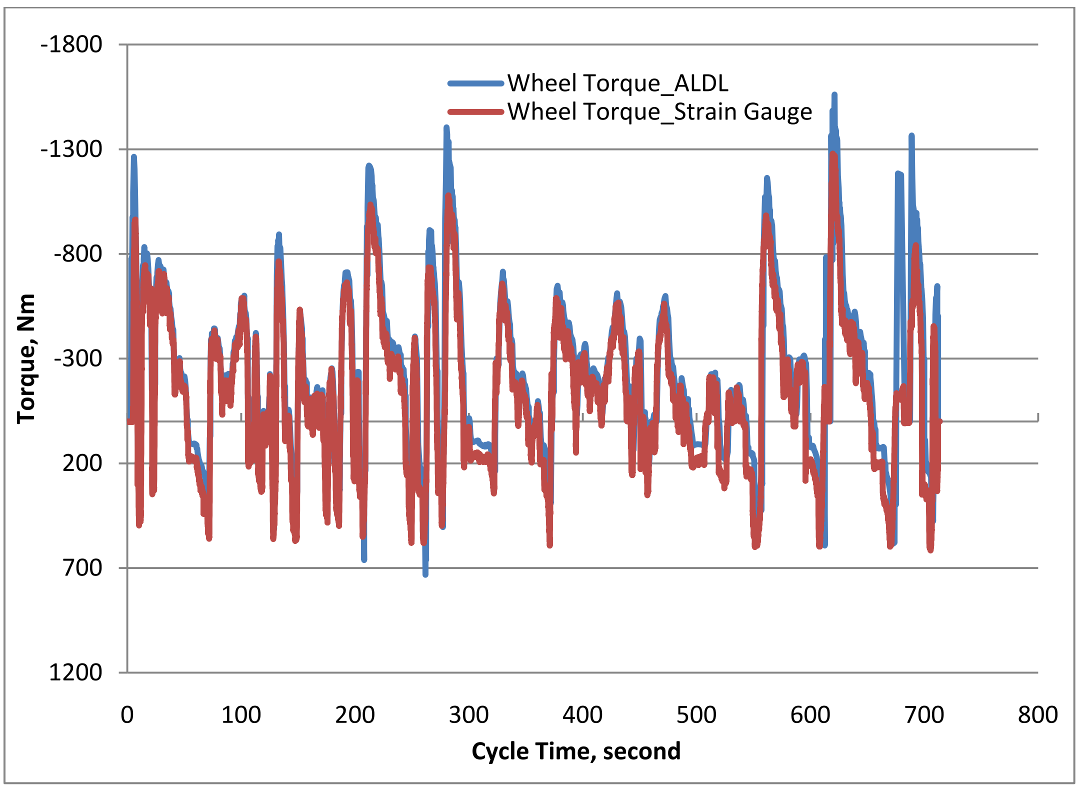

Figure 3-12, Torque output through the drive cycle

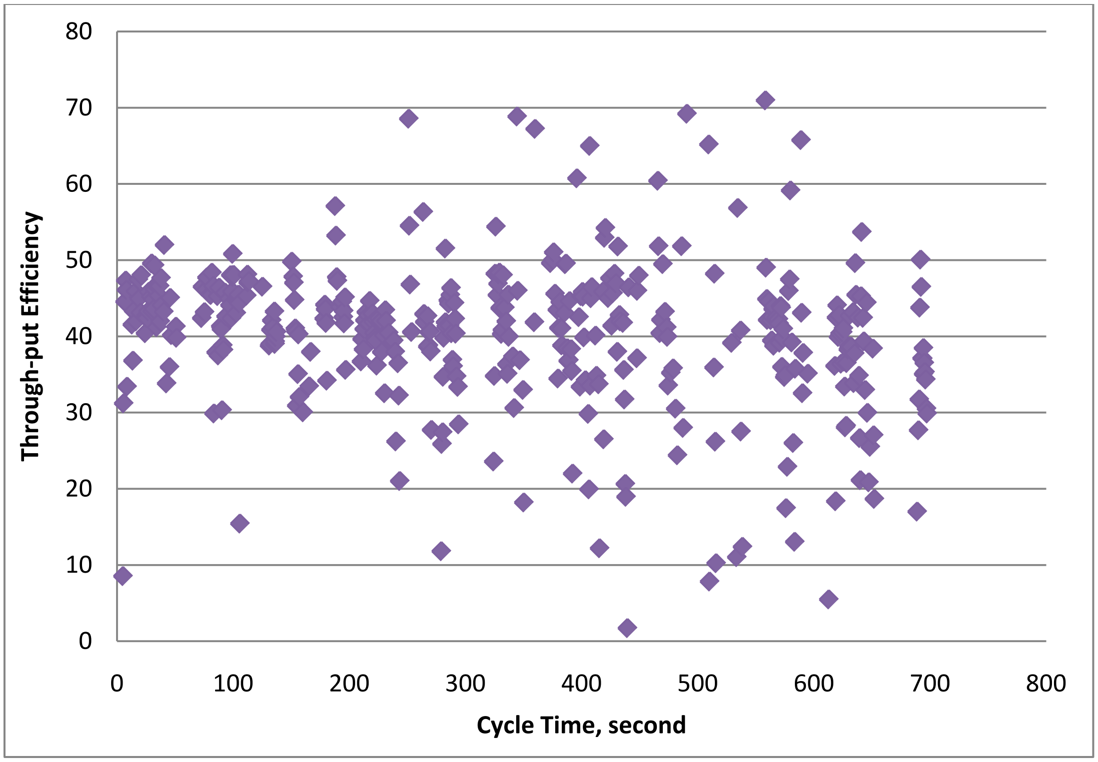

Figure 3-13, Vehicle through-put efficiency through the drive cycle

The torque readings from the strain gauges on the half-shafts and the vehicle's ALDL network are plotted in Figure 3-12, and corresponding through-put efficiency of the vehicle through the drive cycle in Figure 3-13.

With the foregoing backdrop of experience in both modeling and running an instrumented electric vehicle through a drive cycle, the extension of such results to predict performance when using advanced battery chemistries is examined in Section 4.

4. Vehicle Simulations using Advanced Batteries

To reduce transportation emissions and energy consumption, the California Air Resources Board (CARB) adopted the low-emission vehicle (LEV) program in 1998. The Zero Emission Vehicle (ZEV) mandate was included in the program. Under the original ZEV mandate, automakers were required to produce 2% ZEVs by 1998, 5% by 2000 and 10% by 2003. The only commercially available technology for zero tailpipe emission vehicles in the early 90's was the battery electric vehicle.

Starting mid 90's, many major automakers introduced battery electric vehicles to their fleet in the form of evaluation programs, ranging from subcompact coupe, compact SUV to compact pickup truck. First generation EV's produced used lead acid batteries and AC induction motors for their powertrain. Performance of these EV's was not very promising or attractive to most consumers. Second generation products employed nickel metal hydride batteries for improved range, but the autonomy was still significantly less than for conventional vehicles. By 2001, with adaptation of the ZEV rules to technical realities and cost issues, focus shifted to fuel cell and hybrid vehicle technologies.

Since the latest spike in energy prices throughout 2008 and rising concerns over greenhouse gas emissions, battery electric vehicles have again become a popular consideration for alternative transportation. Electric vehicle technology has been established over a century; recent breakthroughs in battery technology have convinced an increasing number of manufacturers that battery electric vehicles are a feasible alternative for the daily commute and possibly even more.

The Powertrain System Analysis Toolkit (PSAT), described in Section 3, uses a driver model to follow the EPA standard driving cycles. Simulations were run to evaluate and compare these results with EVAmerica road test data collected during the 90's on various electric vehicles, to validate the accuracy of PSAT simulations.

4.1. Electric Vehicles in the 90's

Four battery electric vehicles were chosen for simulations, they are the GM EV1, Chevy S-10 EV, Ford Ranger EV, and Chrysler EPIC minivan. For each of these, detailed motor performance, battery technology specifications, and tire data were available, hence good simulations are possible.

4.1.1. GM EV1

The EV1 was introduced by General Motors in 1997. It was a subcompact coupe powered by lead acid batteries during the first generation, equipped with a 102 kW AC induction motor. A second generation, introduced in 1999, offered Ovonic NiMH batteries for weight reduction and better range [EVAmerica].

4.1.2. Chevy S-10 EV

The Chevy S-10 EV was first introduced in 1997 as an electric version of Chevy's S-10 pickup truck. The electric S-10 was fitted with an 85 kW variant of the three phase AC induction motor used in the EV1 produced by Delphi Electronics, and employed the same Panasonic lead acid batteries. The traction battery pack consists of 26 batteries, rated at 312 V and 60 Ah. Peak motor power was reduced to lessen strain on the batteries due to the extra weight the truck had over the EV1, along with higher aerodynamic resistance. The increased duration electrical load would have damaged the batteries otherwise. A NiMH variant with Ovonic cells was also introduced in 1999 [EVAmerica].

4.1.3. Ford Ranger EV

The Ford Ranger EV was first introduced in 1998, powered by EAST-PENN lead acid batteries (39x8V cells rated at 90 Ah) and an AC induction motor, a powertrain similar to that of the S-10 EV, originated by Siemens and Ford Ecostar [EVAmerica].

4.1.4. Chrysler EPIC

Chrysler introduced the EPIC minivan with a lead acid (first generation, 1997) and SAFT nickel metal hydride (second generation, 1999) batteries. This model succeeded the 1993/94 Chrysler TEVAN powered by NiCd and also NiFe batteries [EVAmerica]. Complete test data and motor characteristics were only available for the second generation product with NiMH batteries from EVAmerica.

4.2. EV Baseline Performance Goals

Idaho National Laboratory's Advanced Vehicle Testing Activity (AVTA) examined many full size electric cars in the 1990's, called the EVAmerica testing program. Baseline performance goals were established for the SAE J1634 combined city/highway driving schedule in warm conditions (25°C) and with no accessory loads on. These metrics were set for urban/suburban use in mind. A more complete set of metric is in Appendix A.

Table 4-1, EVAmeria performance baseline

Acceleration 0-50 mph	Maximum Speed	Driving Cycle Range	Recharge Time	Seating Capacity
13.5 sec @ 50% SOC	70 mph in one mile	60 miles	8 hours	2

Road tests and extensive data collection were performed on 21 different electric vehicles to evaluate whether they qualified under the nominal performance targets. The EVAmerica evaluations for electric vehicles took place between 1994 and 2001. There were 33 minimum requirements on vehicle interior, exterior, powertrain, safety, and other factors the vehicle had to meet in order to receive EVAmerica production level readiness status. Road tests focused on the evaluation of dynamic performance for each EV.

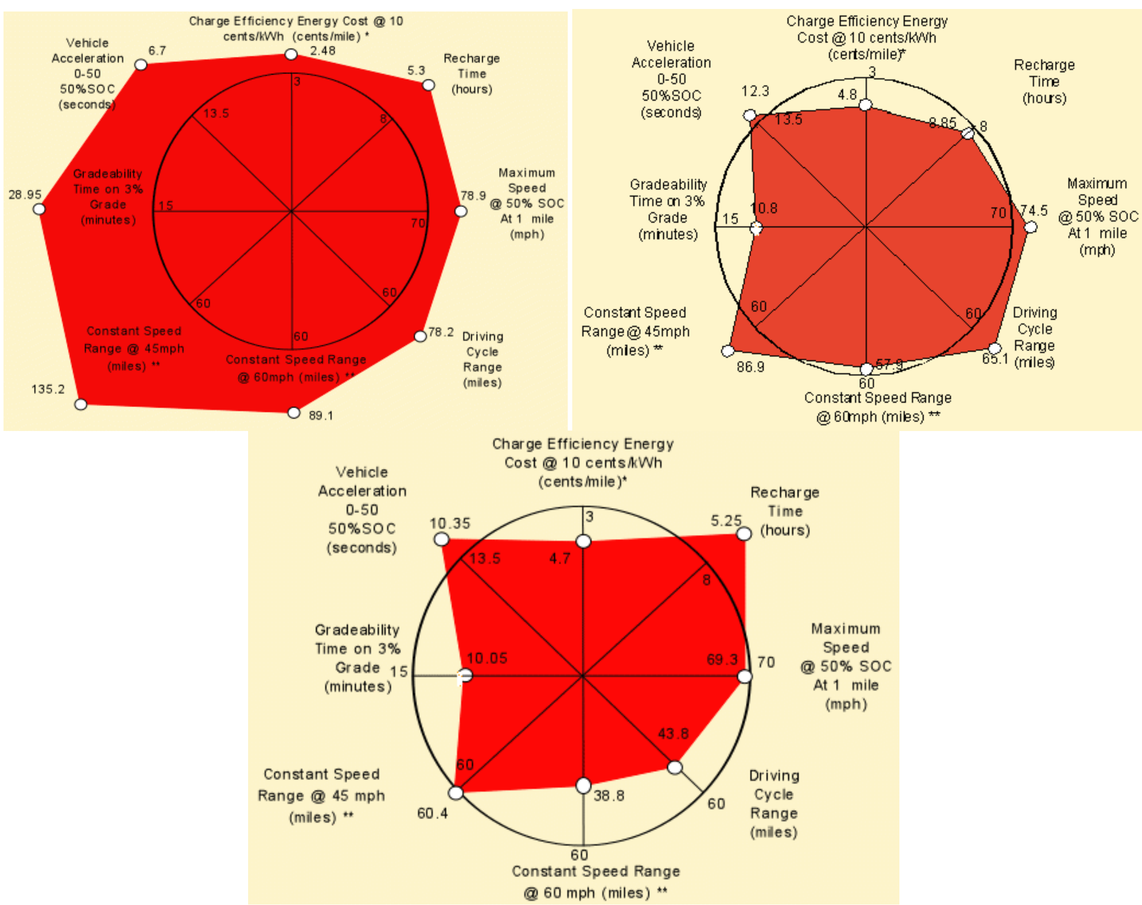

Figure 4-1, Lead Acid vehicles: EV1 (top left), Ranger (top right) and S10 (bottom) road test vs. performance goals [EVAmerica]

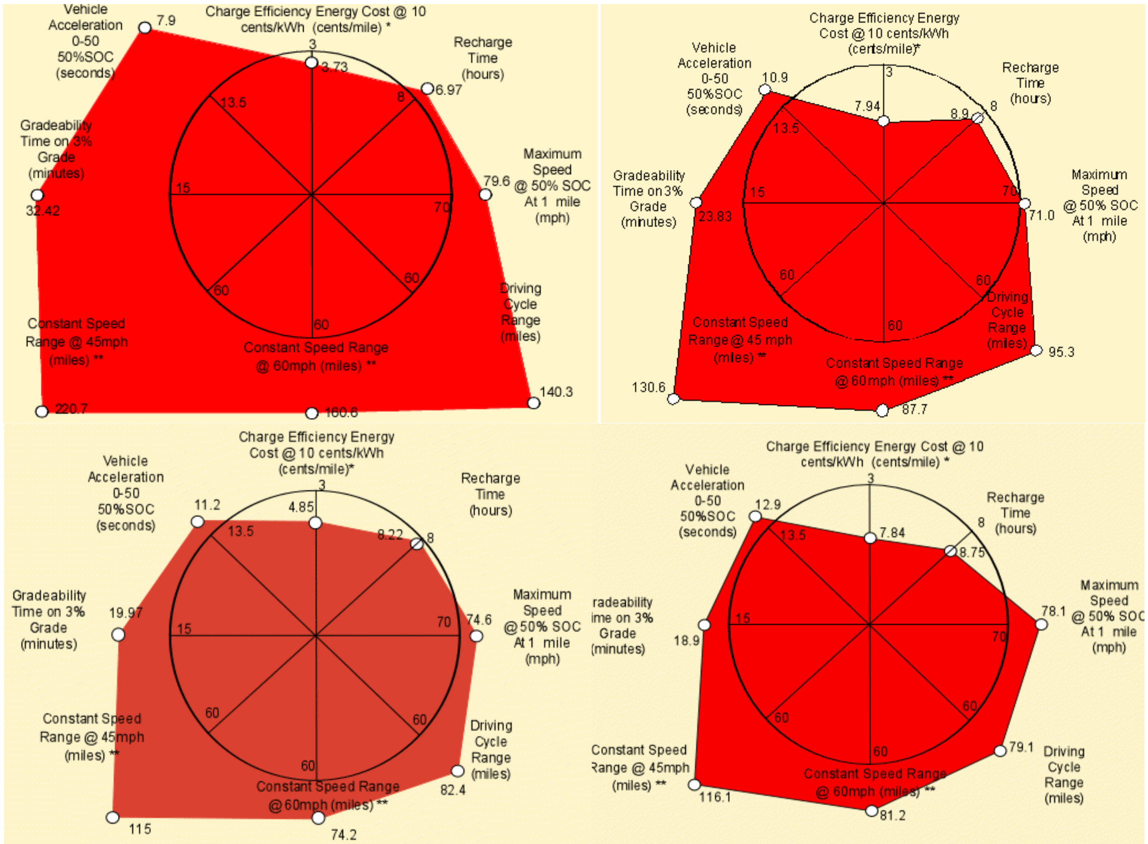

Figure 4-2, NiMH vehicles: EV1 (top left), S-10 (top right), Ranger (bottom left) and EPIC (bottom right) road test vs. performance goals [EVAmerica]

Figures 4-1 and 4-2 depict road test results of EVs with their respective batteries in relation to the major performance goals, including vehicle acceleration 0-50 mph, gradeability time on 3% grade, constant speed range at 45 mph, constant speed range at 60 mph, driving cycle range, maximum speed at 50% SOC at 1 mile, recharge time, and charge efficiency energy cost. The PSAT modeling focused on performance simulation of these electric vehicles, including acceleration at 100% SOC, and energy consumption and range based on the SAE J1634 combined UDDS-HWFET cycle. Pertinent road test results and simulation runs using a refined PSAT model for the four electric vehicles described earlier are summarized in Table 4-2 and 4-3. Appendix B contains vehicle, battery and motor data used in these PSAT simulations.

Table 4-2, EVAmerica road test result for EV with PbA battery

	EVAmerica Test Data				PSAT result		
	Acceleration 0-80 km/h, s	**Energy Consumption,** Wh/km	**Driving Cycle Range*,** km	**Recharge Time**	**Acceleration 0-80 km/h,** s	**Energy Consumption,** Wh/km	**Driving Cycle Range*,**km
EV1	6.3	102	145	5 hrs 18 min	6.3	100	159
S-10	9.75	181	70	5 hrs 15 min	9.5	178	89
Ranger	11.6	209	105	8 hrs 51 min	11.4	204	107

* **EPA unadjusted city/highway results**

Table 4-3, EVAmerica road test result for EV with NiMH battery

	EVAmerica Test Data				PSAT result		
	Acceleration 0-80 km/h, s	**Energy Consumption,** Wh/km	**Driving Cycle Range*,** km	**Recharge Time**	**Acceleration 0-80 km/h,** s	**Energy Consumption,** Wh/km	**Driving Cycle Range*,**km
EV1	6.3	111	225	6 hrs 58 min	5.9	105	237
S-10	9.9	171	153	8 hrs 54 min	9.3	170	155
Ranger	10.3	195	132	8 hrs 13 min	10.1	186	139
EPIC	12.3	203	127	8 hrs 45 min	11.9	229	132

* **EPA unadjusted city/highway results**

4.3. PSAT Simulation Results

Powertrain configurations of the above vehicles were modeled with PSAT using manufacturer's performance specifications of the key drivetrain components. Vehicles were simulated through the same driving cycles (SAE J1634, combined 55% city / 45% highway cycle, unadjusted) as performed on the independent EVAmerica dynamometer tests. Simulation results are shown alongside values recorded by EVAmerica in Table 4-2 and 4-3.

Results of PSAT simulations were all within a 5% tolerance of the EVAmerica road evaluation results with error consistently on the side of over-predicting actual performance. The assumption of a 500W accessory load was made according to the SAE Standard J1634, in that only the basic electronics were running; i.e. no air-conditioning loads. It appears reasonably safe to conclude that PSAT simulation provides an accurate prediction for electric vehicle performance given the proper component data. Further simulations were run to estimate vehicle performance using advanced battery chemistries, summarized in Table 4-4, for the above four vehicles. The vehicle driveline and chassis parameters were held constant, while attempting to "package" the newer cells into the stock battery box.

Table 4-4, Characteristics of different battery chemistries

Manufacturer	Chemistry	Cell Nominal Voltage	Capacity	Mass	Module Dimension	Energy Density		Internal Resistance	
		V	*Ah*	*Kg*	*mm*	*Wh/kg*	*Wh/l*	*mΩ/Ah*	*mΩ/cell*
Panasonic	PbA (EV1260)	2.1 x 6	60	19	388x116x175	37	91	0.037	0.37
SAFT	NiMH	1.2 x 10	93	18.8	195x120x390	65	118	0.09	0.92
Ovonic	NiMH	1.2 x 11	85	18.2	102x176x409	62	165	0.137	1.1
Kokam	Li-Poly	3.7	240	5	325x447x16	177	382	0.0018	0.43
HiPower	LiFePO4	3.2	100	3.5	282x160x50	91	142	0.02	2
A123 cylindrical	LiFePO4 (nano)	3.3	2.3	0.07	12.93(r), 65.15(h)	108	221	3.48	8
A123 prismatic	Li-Poly (nano)	3.3	20	0.48	165x227x7.05	135	245	0.12	2.4
Thunder Sky	$LiCoO_2$	3.6	100	3	145x220x61	120	185	0.022	2.2
Thunder Sky	$LiFMnO_2$	3.7	90	3	145x220x68	111	153	0.032	2.88
LG Chem	$LiMnO_2$	3.85	10	0.243	201x93.6x7.0	158	292	0.1	1

4.4. EVs employing Advanced Battery Technology

Due to the limited energy density and the pronounced Peukert effect with lead acid batteries, vehicles powered by these show the poorest performance. Although nickel metal hydride batteries were subsequently introduced, showing significantly better range and reduced vehicle weight; the NiMH battery was expensive and less efficient during recharge. Its longevity however was a notable improvement over the lead acid technology.

Lithium-ion batteries were first introduced in vehicles at the turn of the millennium (Nissan Altra). Various chemistries and packaging configurations have evolved since.

Table 4-4 gives a summary of key characteristics for a variety of these cell types now commercially available. A very important practical consideration is the volumetric energy density. This parameter is used as a baseline for "retrofit" to existing electric vehicles in this analysis. Table 4-5 shows available cell and pack volume for the various existing vehicles. The available packaging space is generally a practical limiting factor, and the stored energy resulting via an "upgraded" retrofit battery pack, using more advanced technology cells, is thus determined. Table 4-5 gives the resulting energy storage limitations based on different cell types; in all cases resulting in decreased vehicle weight and, hence, reduced energy consumption.

Table 4-5, Battery pack volume and stored energy for each vehicle

Vehicle	**EV1**		**S10**		**Ranger**		**EPIC**	
Pack Volume, m^3	0.205		0.205		0.337		0.256	
	Stored Energy, kWh	**# of cells**	**Stored Energy,** kWh	**# of cells**	**Stored Energy,** kWh	**# of cells**	**Stored Energy,** kWh	**# of cells**
Kokam Li-Poly	82	93	82	93	135	153	103	116
HiPower $LiFePO_4$	31	90	31	90	52	150	39	113
A123 Li-Poly Prismatic	49	776	49	776	79	1276	59	969
Ovonic NiMH	29	26	29	26	28*	25	26	14
Panasonic PbA	18	26	18	26	28	39	N/A	

* OEM vehicle did not utilize full battery box volume.

Table 4-6, PSAT simulation result for EVs with advanced lithium based battery

	Kokam Li-Poly battery			**HiPower LiFePO4 Battery**		
Vehicle	**0-80 km/h,** second	**Energy Consumption,** Wh/km	**Range,** km	**0-80 km/h,** second	**Energy Consumption,** Wh/km	**Range,** km
EV1	5.2	92.6	885	5.7	97.6	317
S-10	8.7	159.1	515	8.9	160.9	192
Ranger	9.4	170.3	481	10	173.4	178
EPIC	11.8	213.1	384	11.2	221.8	139

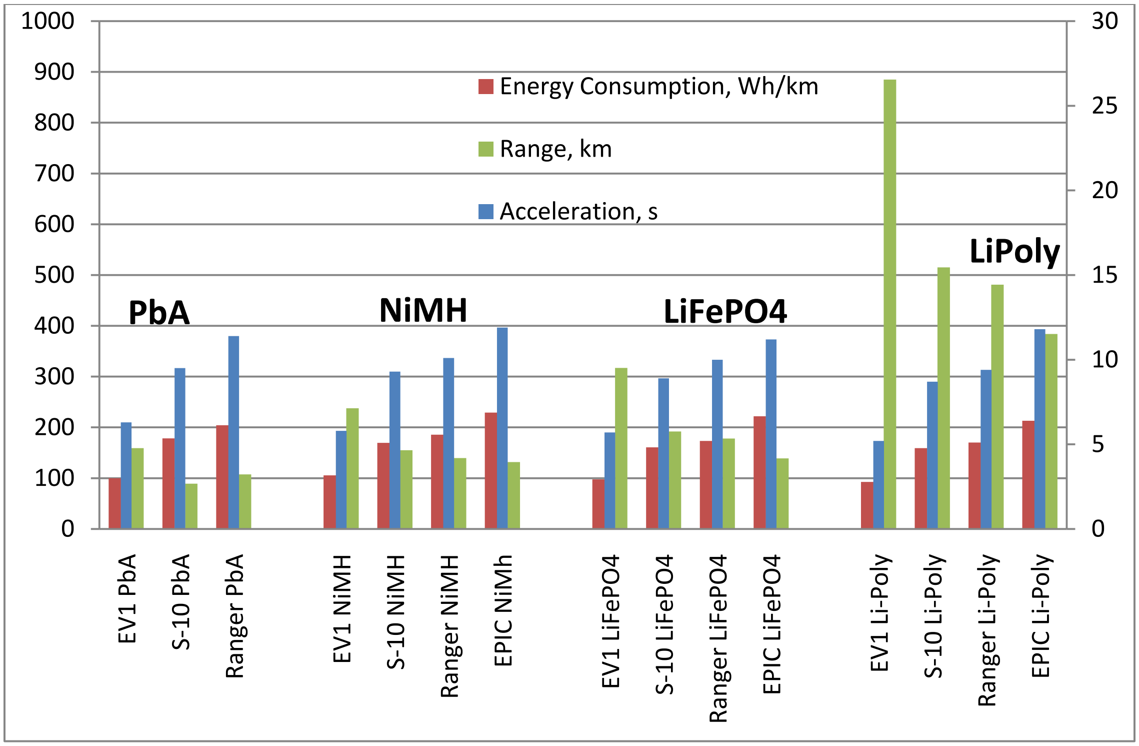

Figure 4-3, Performances of EV1, S-10, Ranger, and EPIC with different batteries

Table 4-6 and Figure 4-3 summarizes some combined drive cycle range and performance results using advanced batteries. For the above simulations, the number of lithium polymer and lithium-ion phosphate cells was estimated by the volumetric constraint. The PSAT results reflect differences in battery pack mass, energy capacity, internal resistance, and overall vehicle weight; while the pack voltage in every case meets the requirements of the motor/inverter and matches the original specifications. With no change to the vehicle's exterior parameters, such as frontal area, drag coefficient, and tire rolling resistance; as expected the lithium polymer battery exhibited superior performance for all cases. A battery's low internal resistance and energy density contribute the most towards vehicle acceleration and energy efficiency. Lithium iron phosphate batteries have better energy density compared to both lead acid and nickel metal hydride batteries, but suffer from a higher internal resistance and lower volumetric energy density relative to lithium polymer batteries, thus generating more losses during operation. Nonetheless, the vehicle range estimations are remarkable, especially for the lithium polymer batteries showing range performance on par with conventional vehicles. Detailed battery data is presented in Section 6 in conjunction with a sensitivity study on performance parameters.

4.5. New vehicle with advanced battery technology

To further estimate the feasibility of lithium based EVs, a design exercise was carried out on a modern crossover vehicle, a 2009 Saturn Vue, modifying it into an EV combining the best of this technology coupled with advanced system packaging. The lithium based battery vehicle variants were simulated using PSAT, using commercially available off-the-shelf technology. The latest generation of electric machines and power inverters were also assumed. Data for the electric motor and inverter were taken from the 4th generation GM fuel cell Electric Traction System (ETS). This is the drive system for the case presented in Table 4-7, using a battery packaging constraint. Fitment is without intrusion into existing passenger or cargo space, nor requiring chassis modifications.

Table 4-7, Saturn Vue simulation results with various batteries and fuel cell ETS motor

Parameters		Battery Chemistry						
		Li-Poly Kokam	**$LiFePO_4$ HiPower**	**$LiFePO_4$ cylindrical (nano-coating) A123**	**$LiFePO_4$ prismatic (nano-coating) A123**	**$LiCoO_2$ Thunder Sky**	**$LiMnO_2$ Thunder Sky**	**$LiMnO_2$ LG Chem**
EPA Driving Cycles	**0-100 km/h,** s	9.5	10	10.8	10.6	10.6	10.2	10.4
	80-112 km/h, s	6.2	6.8	6.3	6.2	6.7	6.4	6.3
	UDDS, Wh/km	160.2	167.4	171.0	170.8	164.3	161.2	168.9
	HWFET, Wh/km	194.2	201.8	194.2	185.7	199.1	197.9	190.0
	Combined, Wh/km	179.9	186.1	185.3	179.5	184.1	181.9	176.9
	US06, Wh/km	287.1	340.3	278.8	317.2	316.8	332.6	178.6
	SC03, Wh/km	259.7	281.5	269.7	280.36	273.1	273.5	275.1
	UDDS cold, Wh/km	172.7	180.7	184.6	188.5	189.6	188.2	188.7
Range, km (Combined)		444	163	220	265	195	166	339

A vehicle powered by lithium polymer cells shows better acceleration and lower energy consumption per unit distance, resulting in better range. A battery volume limitation of 209 liters with a packaging factor of 1.2 was set, determined by detailed packaging studies using the full vehicle CAD model. This is a pack volume almost identical to the S10 and EV1; but substantially less than on the Ranger and EPIC minivan. It represents what can be achieved on a modern midsize vehicle without any compromises on interior space, or chassis re-design specific to EV architecture.

The internal resistance of a $LiFePO_4$ battery is 4.6 times that of the best lithium polymer battery for the case examined, as shown in Table 4-4. Higher internal resistance causes proportionally more voltage drop across the battery terminal under discharge conditions. This voltage drop increases with the increasing rate of discharge (C-rate). A battery with lower internal resistance therefore has a wider zone where there is little fluctuation of DC bus voltage; important for preventing the inverter from dropping off-line under heavy load. High internal resistance causes the cell's voltage to drop prematurely over long discharge cycles, this resistance increases towards a low state-of-charge, and causes internal heating that may affect battery longevity.

The battery is not the only source of differing performance numbers, but the primary factor; motor and inverter characteristics also have effects on vehicle performance. Details on motor and inverter influences are discussed in Section 5 and 6.

5. Electric Motors

The electric machine is a piece of well-developed technology, making it the standard prime mover in industrial applications. Various types of electric motors are available, each with unique characteristics and functionality. Traditionally for vehicles, electric motors convert electrical energy into mechanical energy to provide propulsion. They can also be run in reverse and act as generators to convert mechanical energy back into electrical energy. This is easily accomplished with modern four quadrant controls from a single machine. The electric motor and inverter drive combination is the only propulsion device on an electric vehicle, therefore its characteristics have a great impact on vehicle performance.

5.1. DC Motors

The technology of brushed DC motors is well established with more than a century of use. Brushed DC motors consist of a stationary field and rotating armature/brush commutation system. The field can be series or shunt wound depending on the required characteristics. Controlling the speed of a brushed DC motor is simple, the higher the armature voltage, the faster the rotation. This relationship is linear to the motor's maximum speed. The maximum armature voltage, which corresponds to a motor's rated speed, increases in conjunction with horsepower. In a brushed DC motor, torque control is also straight forward; output torque is proportional to current. If the current is limited, the torque the motor can achieve is also regulated. This makes the motor ideal for delicate applications. One drawback is that DC machines tend to be heavy compared to alternative choices. DC motors perform well at lower power ratings. As the power level rises, problems with high speed operation and brush maintenance become significant. Brushed DC motors have a role in applications below 45kW, above this level; mechanical considerations such as the removal of heat from the rotor become more important. When the motors are partially loaded low operating efficiency becomes a concern too.

Separately excited DC motors were used in the early days of the California ZEV period. For instance, the Chrysler TEVAN (1994); however they have been superseded. The Brushless DC motor is a modern alternative to brushed DC motors and can provide solutions to the above mentioned drawbacks. They are better choices in terms of efficiency and the rotors are relatively easy to manufacture. A more accurate description of the brushless DC motor is "an AC synchronous motor with rotor position feedback providing the characteristics of a DC shunt motor when looking at the DC bus." It is mechanically different from the brushed DC motor due to the absence of the commutator; essentially replaced by an encoder and electronic switching. The rotor is normally made up of laminations with a series of discrete permanent magnets inserted into the periphery. Similar in principle to the synchronous motor, the rotor in this machine locks on to a rotating magnetic field produced by the stator. The rotating field has to be generated by an alternating current. In order to vary the motor speed, the frequency of the 3 phase supply must also be changed; which implies that more complex controllers based on inverter technology have to be used. The synchronism between the rotating field and the rotor is dependent on the encoder position feedback signal, and the high speed electronic switching system it drives. A typical DC motor mated with gear box is shown in Figure 5-1.

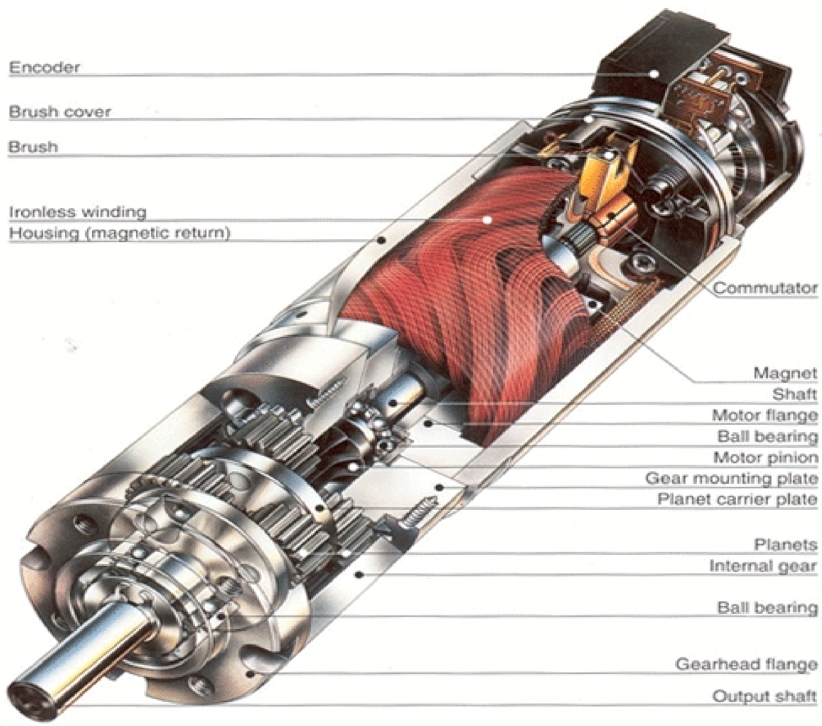

Figure 5-1, Construction of a typical DC motor [Beech Services 2007]

5.2. Induction Motors

The basic design of the AC motor constitutes a series of three windings in the stator with a simple rotor that follows the rotating magnetic field being created. Construction of a typical AC motor is shown in Figure 5-2. The speed of the AC motor depends on three variables: 1. The fixed number of winding sets or poles built into the stator, which determines the motor's base speed. 2. The frequency of the AC voltage supplied, variable speed drives change this frequency to change the speed of the motor. 3. The amount of torque load on the rotor, which causes it to slip and turn slower than the rotating magnetic field of the stator. Through electromagnetic induction, the rotating magnetic stator field induces a current in the conductors embedded in the rotor, which in turn sets up a counterbalancing magnetic field that causes the rotor to turn in the direction of the rotating field. The induced current is proportional to the “slip”, a velocity difference generally less than 5% of the rotating field speed. Off-the-shelf induction motors provide up to about 500kW in output. The AC motor has the advantage of low cost due to its simple rotor construction. This also results in very reliable, low maintenance operation. For fixed speed operation, 3 phase line frequency is used to rotate the stator field, hence its popularity for industrial applications. However, speed and torque control of AC motors can be expensive and inverter costs approach that of brushless DC.

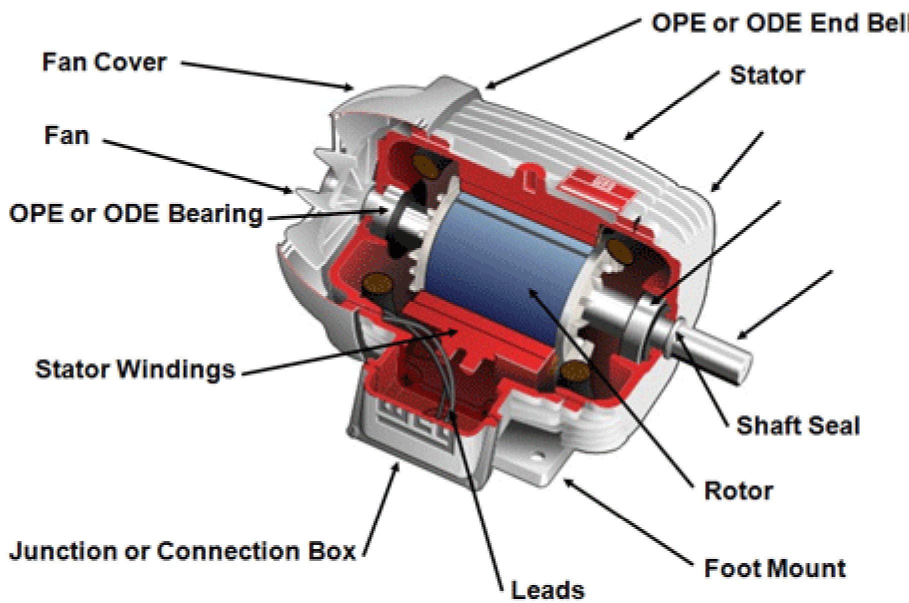

Figure 5-2, Construction of an AC motor [Beech Services 2007]

Due to their torque characteristics, induction motors are a potential choice for hybrid and electric vehicles. These applications require motors that have reasonable starting currents, high starting torque and a very broad constant power operating range. Such objectives can be achieved with an inverter fed induction motor by applying a suitable starting voltage and frequency. The starting voltage chosen determines the current flow proportionally. As speed increases the voltage is raised to maintain current flow in the face of increasing back EMF, and reaches its maximum at the "base speed". With increase of the operating frequency, the iron core loss (magnetic circuit loss) first increases then decreases. At base speed, the point at which the torque begins to fall off and the motor enters the constant power regime, the iron core losses reach their maximum. The copper loss (wire resistive loss) varies slightly with the change of frequency. The iron core loss is more than the copper loss near base speed and less than the copper loss at low and high speeds, which flattens the efficiency curve over the whole operating range. Figure 5-3 shows the iron loss vs. frequency for a typical induction motor, where f_N and f_1 is the rated and maximum frequency, respectively. Modern phase vector based inverters employ phase angle adjustment in real time to optimize the power output over a broad operating range.

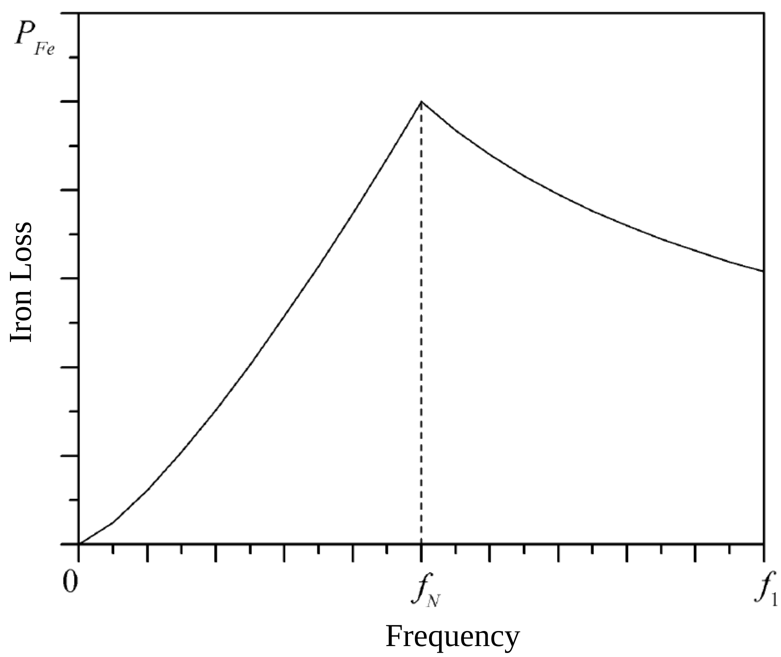

Figure 5-3, Iron loss vs. frequency for induction motor [Wang 2005]

5.3. Synchronous Machines (Brushless DC)

The AC synchronous motor gets its name because the rotor rotates in synchronism with the rotating magnetic field produced by the polyphase electrical supply. Such machines are more expensive, requiring strong magnetic materials in the rotor and an encoder for positional feedback coupled with high speed signal processing on the inverter side. By comparison, induction motors require only a velocity feedback, however the power density (compactness) of the AC synchronous motor is superior to the induction machine. Also because they employ permanent magnets, their efficiency is inherently higher than an induction machine. Such embedded permanent magnet machines are the trend at the current time and form the basis of most hybrid drive systems on the market.

5.4. Electric Machines Modeled

During the electric vehicle era starting in the mid 90's, AC motors were widely used in automotive applications because they were more power dense and reliable than DC motors. The OEM electric vehicles from the 90's examined in the previous section were all equipped with AC induction motors. A good representation is the electric machine used on GM EV1. With peak power of 102 kW, a top speed of over 12000 rpm, and efficiency close to 90%, it was demonstrated that such electric drives were capable of delivering a level of dynamic performance comparable to conventional IC engine vehicles. An alternative is the permanent magnet brushless DC motor, which has become more popular recently. These form the basis of most hybrid drives as mentioned. Such electric motors generally show peak efficiency above 90%. Even though there have not been any significant breakthroughs in motor technology, increased efficiency improves the overall functionality. Inefficiency translates into cooling requirements, thus smaller motor size, reduced weight and less support for cooling needs are the advantages observed in practice. The permanent magnet motor has slightly better efficiency compared to the induction machine; therefore it has started to replace induction motors in EV applications. Figure 5-4 shows an efficiency map of a permanent magnet motor with maximum efficiency of 96%, and Figure 5-7 shows that of an older induction motor with a maximum efficiency of 87% for comparative purposes.

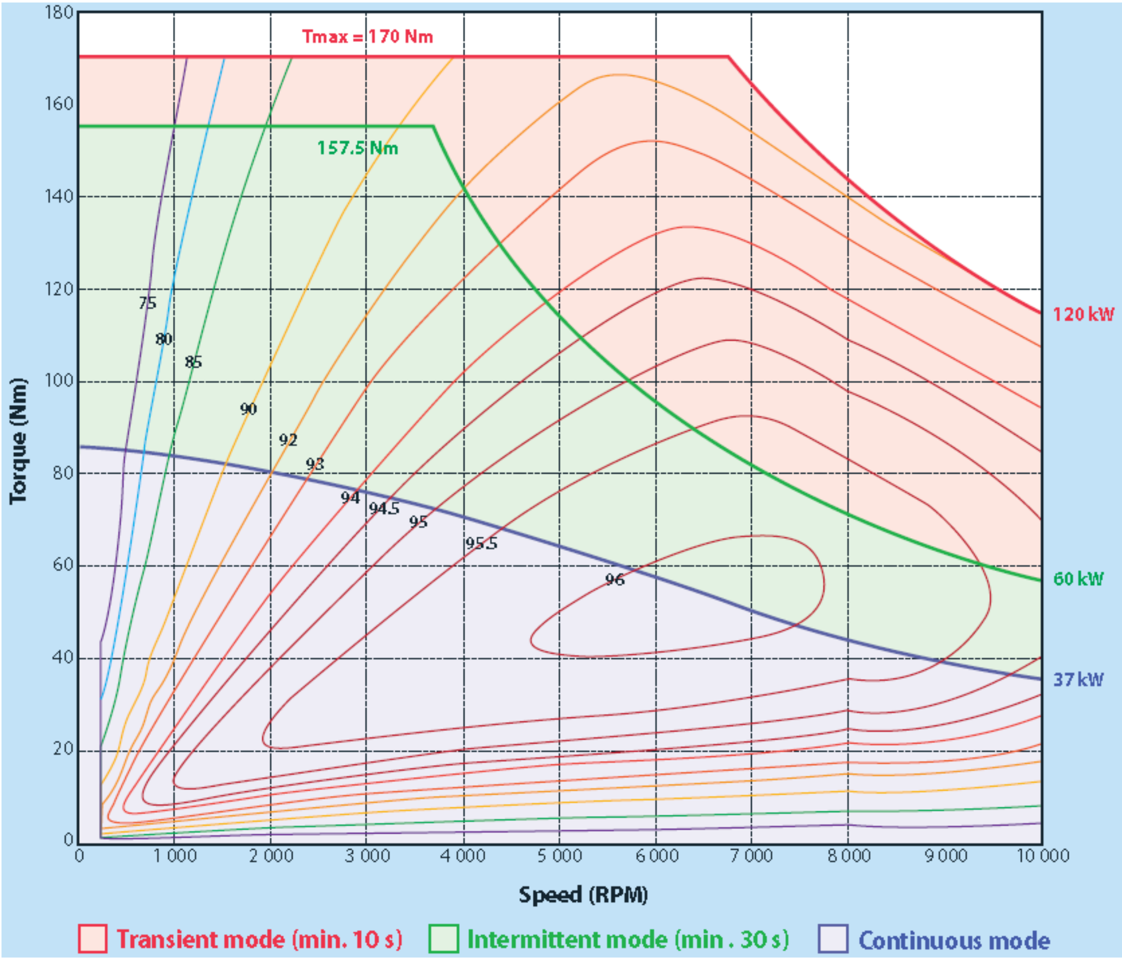

Figure 5-4, TM4 motor efficiency map [TM4 Permanent Magnet Electric Motor specification]

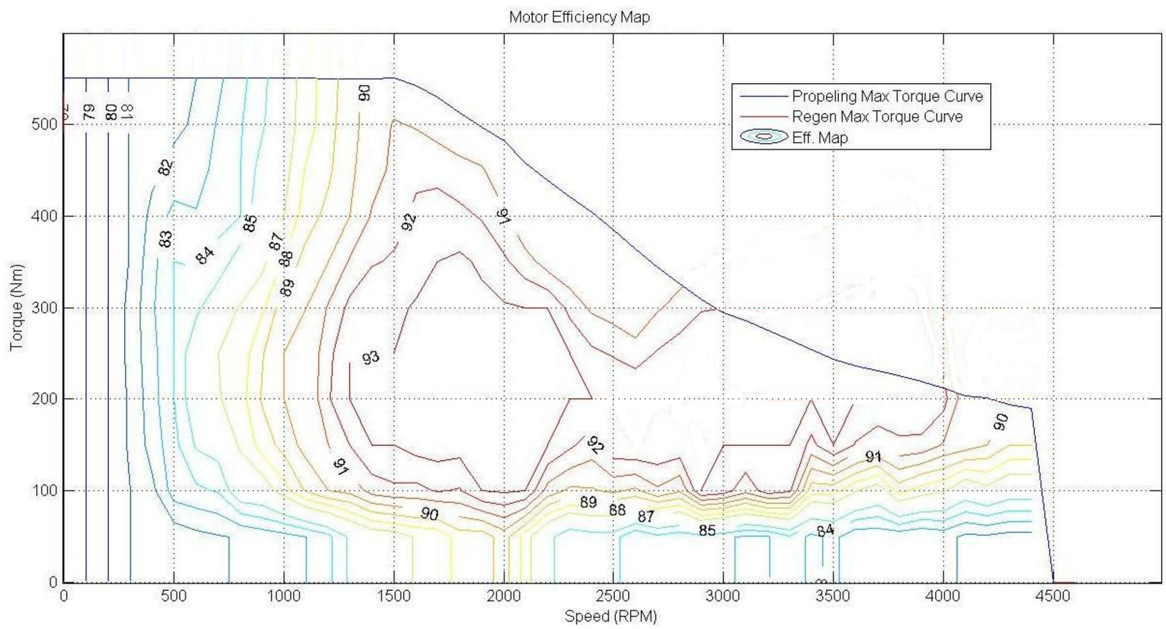

Figure 5-5, UQM PowerPhase 100

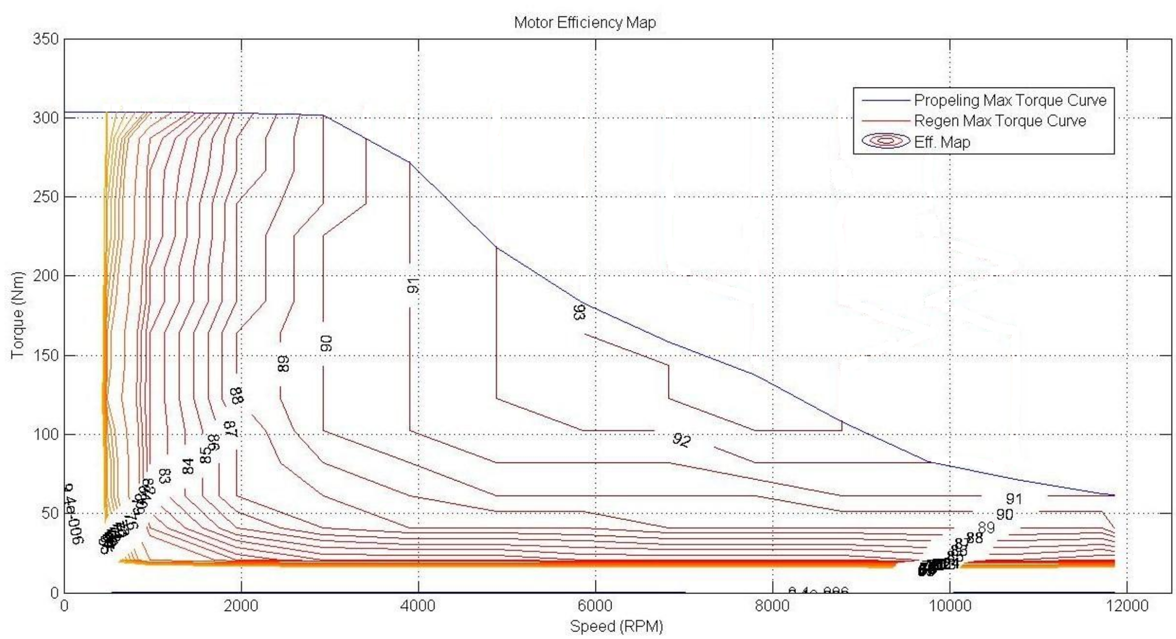

Figure 5-6, GM Fuel Cell ETS GMT101X

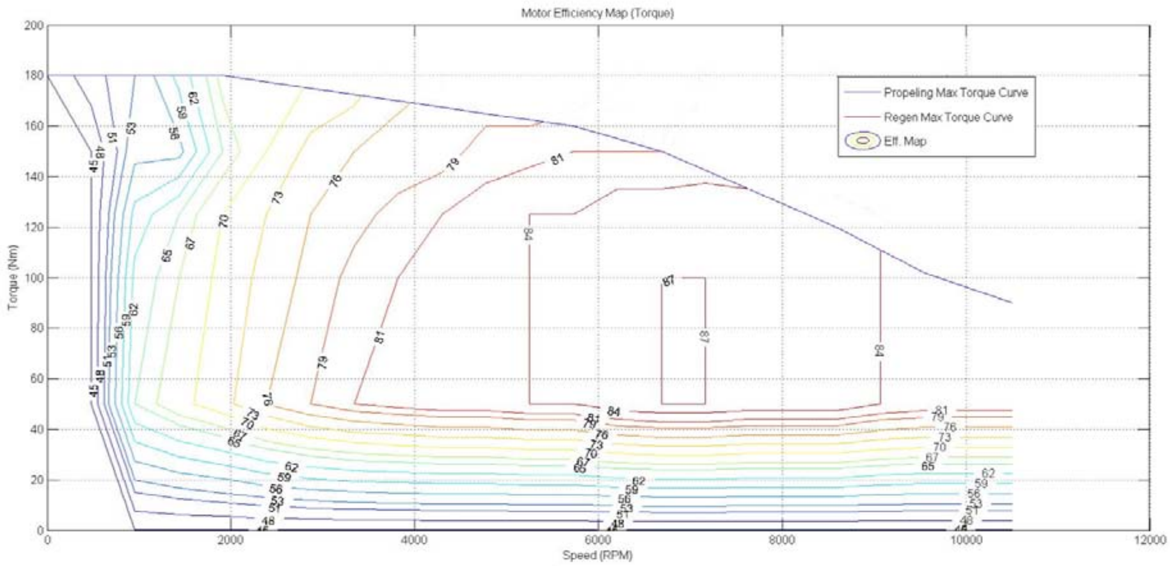

Figure 5-7, EV1 motor efficiency map, Delco System 110

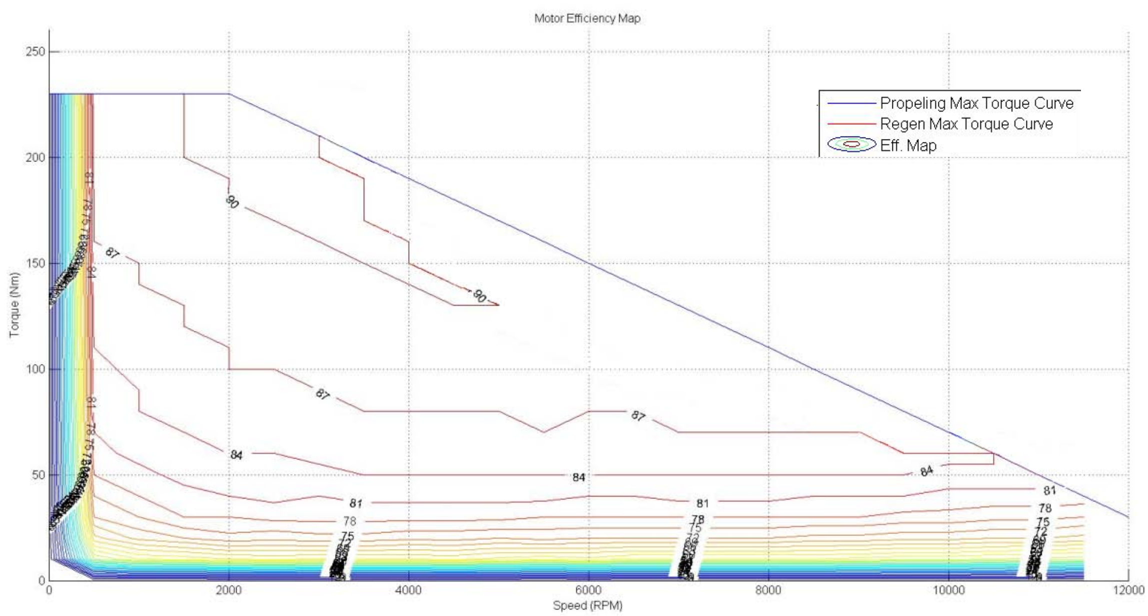

Figure 5-8, Siemens IPT/5134

Such motors do not operate alone on a vehicle, unlike induction motors fed by line frequency in an industrial setting. Thus it is the motor/inverter combination that matters. Improvement in inverter technology; especially the IGBT power stage, contributes to the betterment of propulsion system efficiency.

Vehicle speeds change constantly to adapt to the road and traffic conditions, therefore motor velocity and torque demand is varying. It is important to achieve high efficiency over a broad range, thus comparing peak efficiency is not necessarily indicative. The task of the inverter is to generate a variable frequency and amplitude 3 phase current. Inverters use Pulse Width Modulation (PWM) techniques to generate a sine wave [Siemens 2004]. The applied voltages are changing from zero to a maximum with variable duty cycles, but current through the motor windings cannot change instantaneously because of inductance, thus averaging the voltage and current value over time.

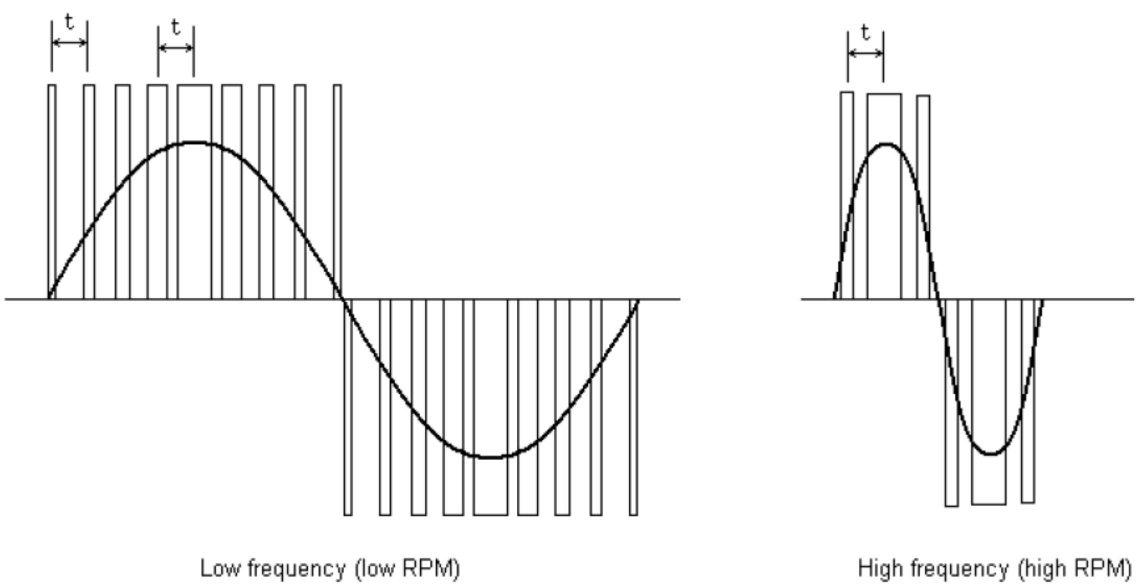

Figure 5-9, Simulated sine wave from PWM [Siemens 2004]

Modern inverters use fast switching Insulated Gate Bipolar Transistors (IGBT) to increase the number of pulses per second to more closely simulate a sine wave and to reduce noise generated. 6-12 kHz is a typical base switching speed on a modern inverter, but this can vary and be reduced to lessen heat generation.

5.5. Motor Modeling Results

PSAT simulations were done on an advanced compact crossover, a 2009 Saturn Vue, illustrating the effect of motor/inverter characteristics on vehicle energy consumption over the EPA standard drive cycles. The Kokam lithium polymer battery was used to model the traction battery characteristics. Table 5-1 summarizes the electric machine characteristics modeled.

Table 5-1, List of traction motors simulated

Motor	**Technology**	**Power,** kW **(cont/peak)**	**Torque,** Nm **(cont/peak)**	**Max speed,** RPM	**Overall Gear Ratio**
Delco System 110	Induction	40/103	180	12,000	10.946
Siemens 5134	Induction	34/90	90/239	10,000	9.091
MES DEA	Induction	40/100	132/200	10,000	9.091
GMT101X	Permanent magnet	80/112	266	12,000	9.760
TM4	Permanent magnet	37/60	60/157	10,000	9.091
UQM PowerPhase 100	Permanent magnet	55/100	400/550	5,000	4.545

Table 5-2, Vehicle performance simulation with induction and PM motor

Parameters		**Induction motor**			**PM Brushless DC Motor**		
		Delco System 110	**Siemens 5135**	**MES DEA**	**GMT101X**	**TM4**	**UQM PowerPhase 100**
EPA Drive Cycles	**0-100 km/h,** s	12.6	12.9	12.8	9.5	10.6	12.3
	80-112 km/h, s	6.4	6.8	6.1	6.2	4.8	5
	UDDS, Wh/km	175.9	178.4	155.0	160.2	168.9	148.1
	HWFET, Wh/km	192.6	192	198.2	194.2	175.4	185.9
	Combined, Wh/km	185.5	186.9	177.9	179.9	172.7	170.0
	US06, Wh/km	297.4	290	294.9	287.1	269.0	260.5
	SC03, Wh/km	276.0	282.2	259.8	259.7	277.4	243.7
	UDDS cold, Wh/km	189.8	191.7	176.6	172.7	182.6	166.3
	Towing*, Wh/km	548.6	557.0	526.4	507.86	474.8	474.0
Range, km (Combined cycle)		430	427	449	444	462	470

* 680 kg trailer on 3.5% grade

The Delco System 110 on the EV1/S-10 EV, Siemens PV5135 drive on Chrysler EPIC, MESDEA system on Renault Kangoo are all propulsion systems with an AC induction motor, while the other three are permanent magnet based designs used for prototype electric, fuel cell and hybrid vehicles. Table 5-2 summarizes the vehicle performance estimates using various drive systems. Vehicle range on the Combined Cycle indicates the trend of increasing range with more advanced motor technology, yet with the new generation of induction machine and inverter (MES DEA), the advantage of the PM motor is not that significant. Section 6 covers the influence of motor efficiency on a vehicle's overall energy consumption in greater detail.

6. Sensitivity Study

Vehicle fuel economy is closely related to parameters such as curb weight, aerodynamic drag, and tire rolling resistance. Electric vehicle performance examined in this section is determined by the powertrain efficiency which includes battery and motor efficiency, other factors are accessory loads and drive cycles. This chapter focuses on the impacts these factors have on electric vehicle range.

6.1. Battery

The batteries used for vehicle traction applications are under short, heavy current loads during acceleration, relative steady current load when cruising, or long heavy current draws when climbing a grade. They also see short intermittent bursts of regenerative braking charging. One parameter that determines how the battery will perform is its internal resistance, this partially determines the battery's "runtime", Figure 6-1. Under high discharge rate, internal resistance will cause voltage drop and the battery pack will show low charge levels while the same battery would deliver more net energy if it were discharged at a slower rate, the Peukert effect [Buchmann 2009].

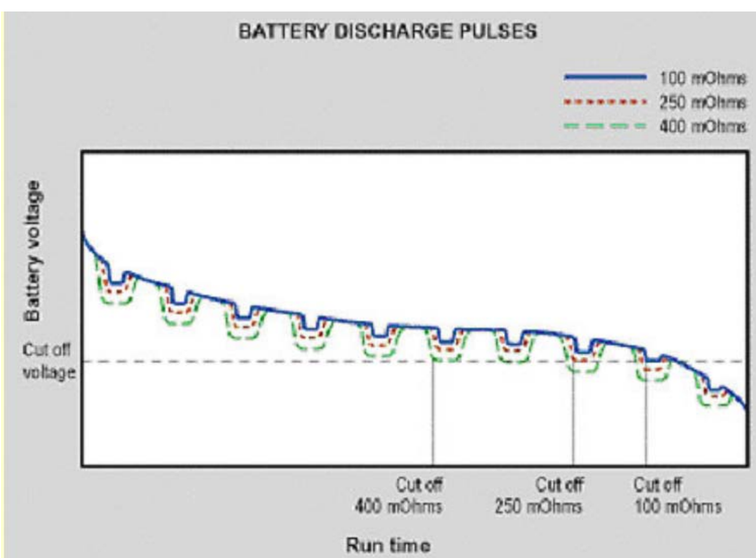

Figure 6-1, Batteries with same capacity but different internal resistance under load [Buchmann 2009]

Figure 6-1 illustrates how a battery with the same capacity but different internal resistance behaves under pulse loads. A battery with high internal resistance consumes more power internally and reaches the cutoff voltage earlier under load.

For any battery chemistry, the internal resistance changes under operating conditions, such as, temperature, discharge rate (C-rate), state-of-charge (SOC) and aging of the battery. The first three conditions are relatively easily modeled and tested. Figure 6-2 and 6-3 show the discharge of a lithium polymer battery under different temperatures and discharge rates respectively. The detrimental effects are multiplicative when both conditions are seen simultaneously.

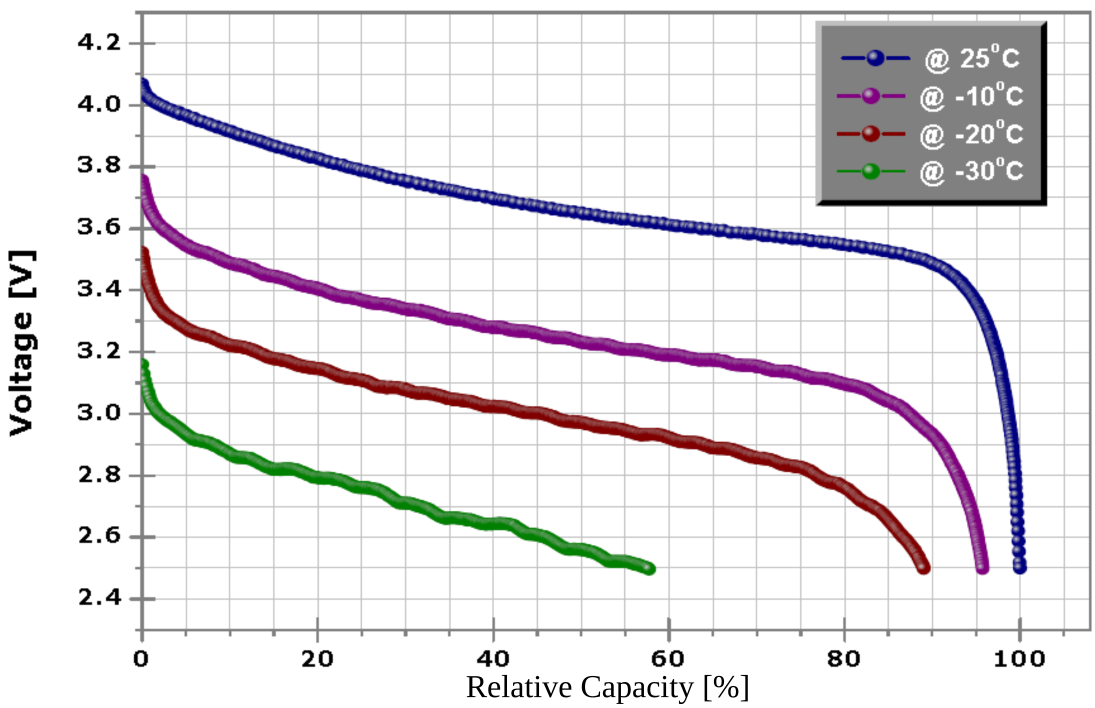

Figure 6-2, Temperature characteristics of Li-poly battery [Kokam 2008]

While the optimum operating temperature of most lithium based battery chemistry is 25-30°C, conditions outside this optimal range results in reduced power performance, especially towards the cold side.

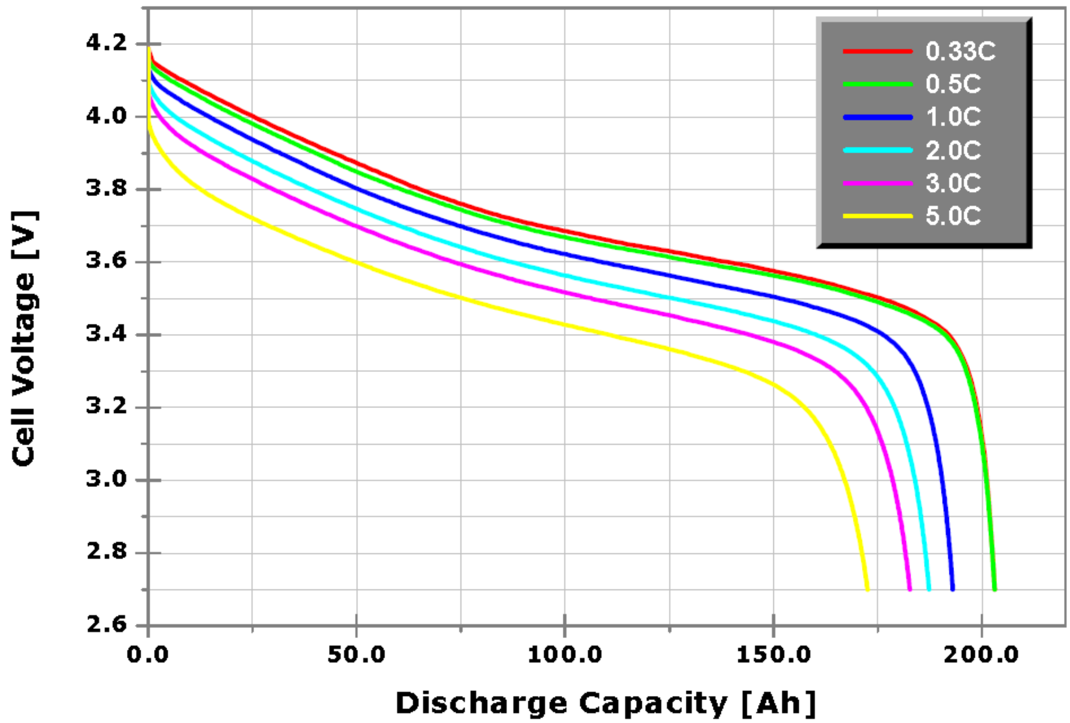

Figure 6-3, Discharge characteristics of Li-poly battery [Kokam 2008]

Figure 6-4 shows internal resistance readings of a nickel-metal hydride battery at different states-of-charge. Continuous charge/discharge cycles produce high internal resistance at a fully charged state, while resting the battery between cycles produces better results. For both NiMH and lithium chemistries, the lowest internal resistance exists at approximately 40-60% SOC, with increasing tendencies at either end of the SOC range.

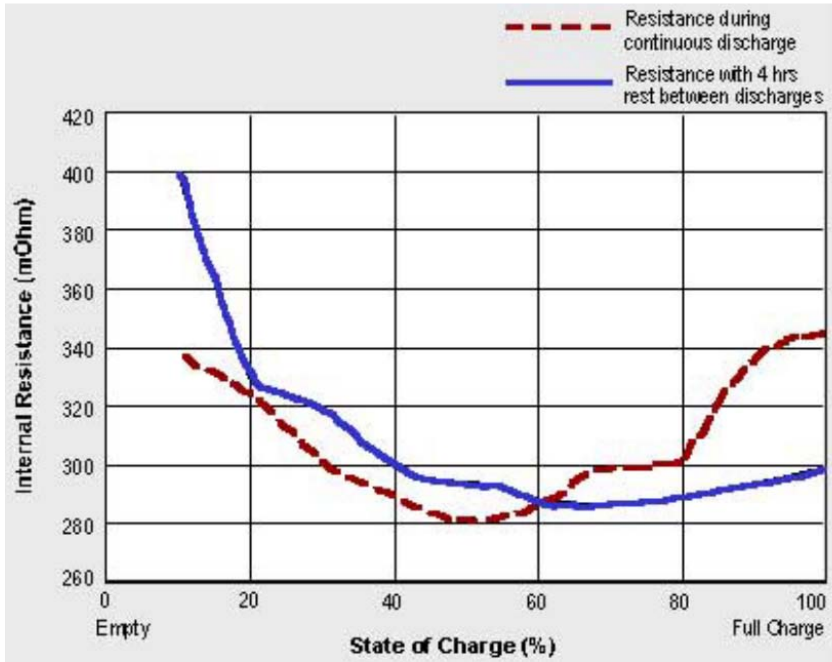

Figure 6-4, Internal resistance of a nickel-metal hydride battery at different SOC [Buchmann 2009]

To investigate the effects of battery resistance on electric vehicle range, simulations were performed by gradually increasing the internal resistance of a lithium polymer traction battery pack to simulate aging. The test vehicle simulated was the advanced compact crossover (Saturn Vue), basic vehicle specifications are listed in Appendix B.

Table 6-1, Simulation results of varying Battery R_{int}

	R_{int} 1x	R_{int} 2x	R_{int} 4x	R_{int} 8x	R_{int} 16x
UDDS, Wh/km	160.2	163.3	168.2	178.9	219.3
HWFET, Wh/km	194.2	196.9	201.3	210.3	221.8
US06, Wh/km	267.1	277.1	294.4	342.7	416.0
SC03, Wh/km	259.7	262.0	271.1	292.6	366.3

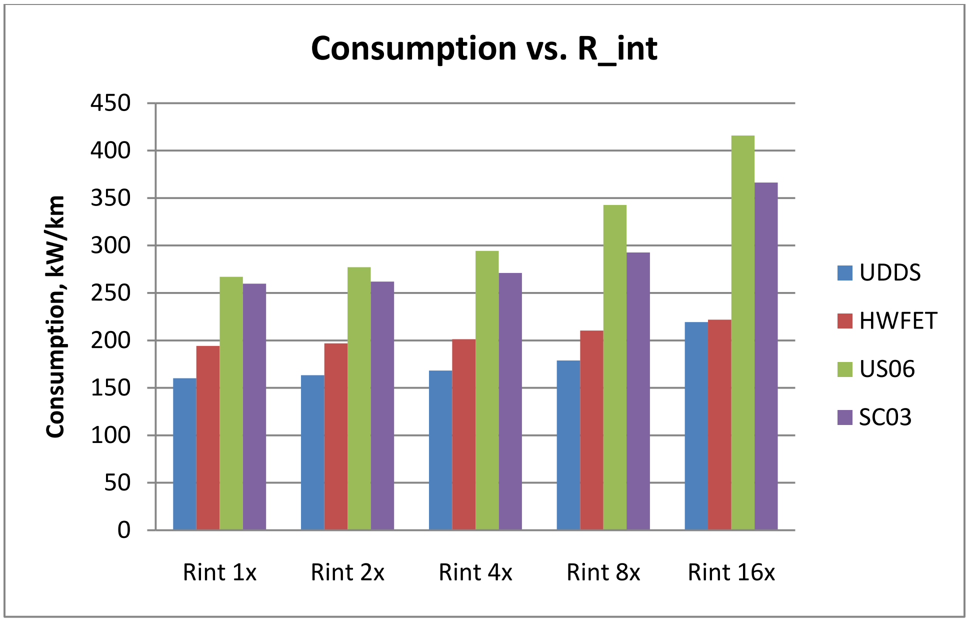

Figure 6-5, Increase of energy consumption with battery R_{int}

Energy consumption shows a linear and gradual increase with battery internal resistance. At eight times the baseline, consumption through drive cycles increase by a weighted average of 10%. Thus advanced batteries do not show immediate concern for range with increases of internal resistance over time. With the aging of the battery this is a normal characteristic, however retention of energy capacity would ultimately determine the life span of the traction battery and it would appear that a gross failure in capacity retention becomes the dominating influence. It should be noted however that increases of internal resistance accentuate battery heating, thus accelerating degradation rate.

6.2. Motor efficiency

Electric motors are known to be efficient, generally above 90% peak conversion efficiency as opposed to 35% or less for most gasoline internal combustion engines. Improving a motor's peak efficiency presents diminishing returns, but there are still variations between different technologies. Permanent magnet based motors generally have a few percent gain in efficiency over induction machines, other things being equal.

The full load efficiency of electric motors also tends to vary with size. As an example, Table 6-2 presents peak efficiencies of industrial induction motors (no inverter) at line frequency. The typical OEM electric vehicles examined earlier would be sized around 50 hp continuous output. With inverter, as required for a variable speed drive, net efficiency would be around 92% (95% for the best available permanent magnet motor technology.) The inverter itself is approximately 97-98% efficient.

Table 6-2, Peak motor efficiency of different motor size

Size (hp)	Pre-EPAct[a]	EPAct[b]	NEMA Premium[c]
1.0	76.7	82.5	85.5
1.5	79.1	84.0	86.5
2.0	80.8	84.0	86.5
3.0	81.4	87.5	89.5
5.0	83.3	87.5	89.5
7.5	85.5	89.5	91.7
10.0	85.7	89.5	91.7
15.0	86.6	91.0	92.4
20.0	88.5	91.0	93.0
25.0	89.3	92.4	93.6
30.0	89.6	92.4	93.6
40.0	90.2	93.0	94.1
50.0	91.3	93.0	94.5
60.0	91.8	93.6	95.0
75.0	91.7	94.1	95.4
100.0	92.3	94.5	95.4
125.0	92.2	94.5	95.4
150.0	93.0	95.0	95.8
200.0	93.5	95.0	96.2

Motor efficiencies at a given speed change as the load varies. Figure 6-6 gives some indication showing off-peak performance as a function of motor size.

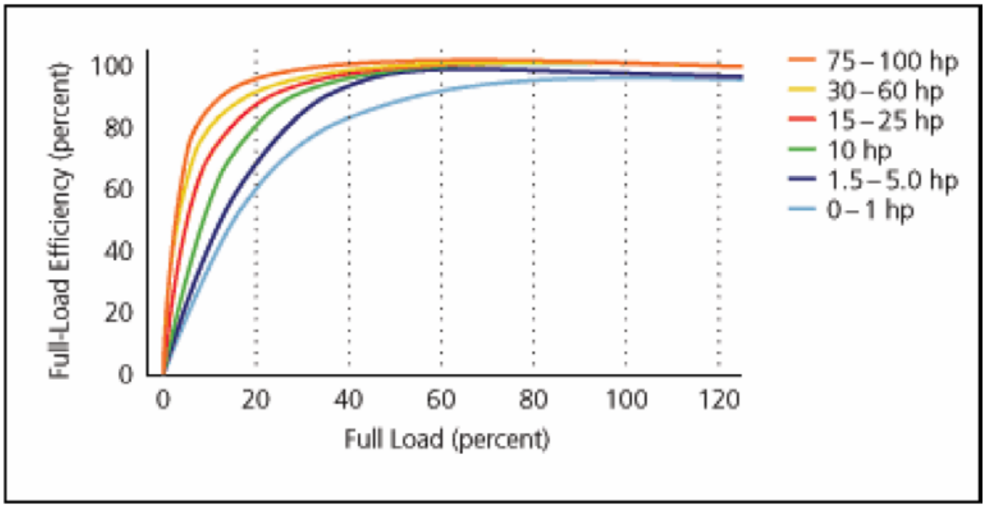

Figure 6-6, Induction motor efficiency varies with the load [NRCAN 2003]

Because in electric vehicles motor and the matching inverter are regarded as the "propulsion system", inverter characteristics contribute to the overall efficiency. Older inverters used a lower switching frequency, causing audible hum, and more inverter heating as a result of the IGBT switches then available, which decreased efficiency. Today's inverters have a switching frequency of up to 20 kHz due to better IGBTs, and eliminate audible hum. The motor current is also more steady through the speed range, giving electric vehicles a smoother start.

Results of increasing a motor's peak efficiency, in increments of 2% for the induction motor, are summarized in Table 6-3; permanent magnet motor results are summarized in Table 6-4. They relate the effect of motor efficiency on electric vehicle energy consumption and range. The converted Saturn Vue for the EcoCAR project was used as a baseline test case with the motor efficiency values scaled upwards. Delco System 110 (induction) and GMT101X (permanent magnet) were the basis for comparisons.

Table 6-3, Simulation results for various motor efficiencies (Delco System 110) on Saturn Vue

	η = 90%	η = 92%	η = 94%	η = 96%
UDDS, Wh/km	173.4	167.0	161.1	154.9
HWFET, Wh/km	204.5	199.5	195.6	190.2
US06, Wh/km	286.6	277.4	267.1	260.2
SC03, Wh/km	271.8	264.6	257.6	251.0

Table 6-4, Simulation results for various motor efficiencies (GMT101X) on Saturn Vue

	η = 94%	η = 95%	η = 96%	η = 97%	η = 98%
UDDS, Wh/km	160.2	158.2	155.3	152.5	149.7
HWFET, Wh/km	194.2	191.4	189.2	187.0	184.9
US06, Wh/km	287.1	283.0	278.5	274.2	269.9
SC03, Wh/km	259.7	255.4	252.1	248.9	246.1

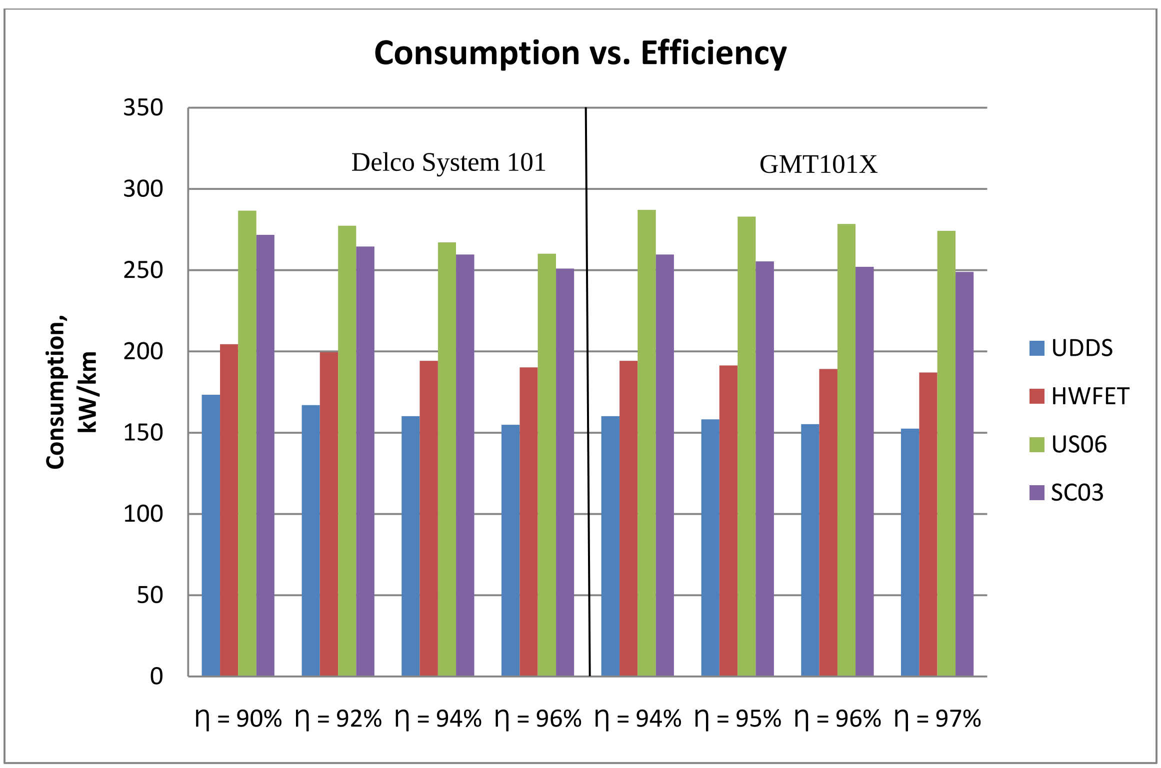

Figure 6-7, Energy consumption through drive cycles as motor efficiency increases (Delco System 110 and GMT101X)

The permanent magnet motor is advantageous over the induction machine simply because it is more efficient without the loss to slip. Increasing motor peak efficiencies over small increments shows that reduction in energy consumption over standard drive cycles is marginal, with an expected reduction of ~1.5% for every 1% peak efficiency gain of the motor.

More important is the time averaged off peak performance. Time weighted torque and speed through the drive cycles shows more about the effect of motor selection as seen previously in Tables 5-1 and 5-2. The HWFET cycle appears to have the least influence on motor efficiency improvements. A drive system's efficiency involves secondary factors, including cost, manufacturing capability, packaging, and weight.

6.3. Accessory load

Accessory loads can have significant impact on a vehicle's fuel economy. OEM fuel economy ratings are based on EPA standard city and highway drive cycles, which are performed with no important accessory load. The reality is that the power necessary to operate accessory loads, such as the air-conditioning compressor, are significant. This can in some instances be greater than the engine power required to move a mid-size vehicle at a constant speed of 56 km/h (35 mph). The size of the air-conditioning system is determined as a consequence of the peak thermal load in the vehicle. The peak thermal load is related to the maximum temperature the cabin will reach while soaking in the sun and the temperature pull-down rate the manufacturer expects to achieve. Although actual use of air-conditioning varies depending on climate, size of vehicle, sun exposure, vehicle occupancy, and consumer habit, such traits have been studied. A conservative assumption is that a vehicle gets used 41 minutes per day, 365 days a year, or 249 hours annually. Estimates of air-conditioning "on time" range from 107 to 121 hours per year, which represents 43 - 49% of vehicle usage. This alone results in an annual consumption of 235 liters of gasoline per vehicle, for operating the air-conditioning system [Farrington 2000].

New EPA 5 cycle test regulations have included air-conditioning and cold starts in the drive schedule to assess fuel economy. A supplemental Federal Testing Procedure, SC03 has been introduced for AC loads.

Table 6-5, A/C supplemental test procedure

Drive Cycle	**SC03**
Time, s	594
Maximum speed, km/h	88.2
Distance, km	5.8
Contribution to total emissions on conventional vehicles	37%

To analyze the impact of air-conditioning, the largest of the accessory loads, on the range of an electric vehicle, simulations were done using the same compact crossover (Saturn Vue) as in previous simulations. Power is delivered by a permanent magnet brushless DC motor (ETX101) and Kokam lithium polymer battery pack (79.9 kWh). EPA unadjusted consumption results are listed in the Table 6-6 for UDDS, HWFET, US06 and SC03.

The maximum thermal cooling load was assumed to be 6 kW. The net Coefficient of Performance (COP) of the electrically driven air-conditioning system was assumed to be 2. This yielded a maximum electric load for the A/C system of 3 kW. This load was then added to the baseline value of 500W (daytime running light, electric power steering, and other electronics) in increments of 1000W. Results are summarized in Figure 6-8.

Table 6-6, Simulation results with different air-conditioning loads

	500 W (base load)		1500W		2500W		3500W	
	Consumption, Wh/km	**Range,** km	**Consumption,** Wh/km	**Range,** km	**Consumption,** Wh/km	**Range,** km	**Consumption,** Wh/km	**Range,** km
UDDS	160.2	498	194.4	411	222.2	359	236.0	338
HWFET	194.2	411	208.5	383	228.1	350	251.7	317
US06	267.1	299	282.5	282	296.4	269	310.3	257
SC03	166.6	479	196.9	405	227.3	351	259.7	307

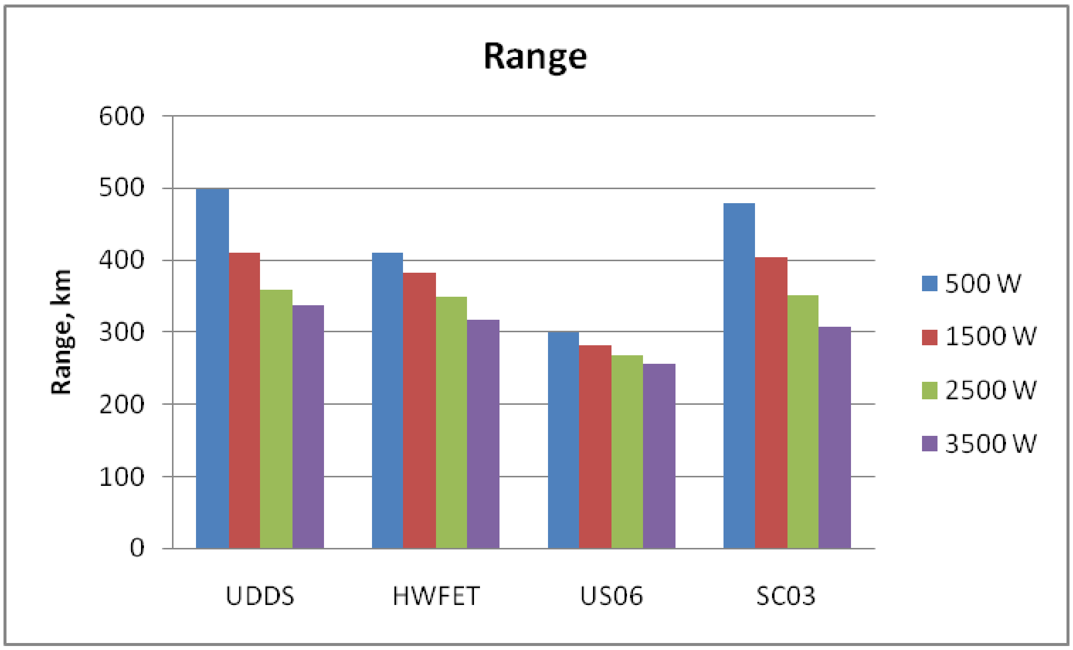

Figure 6-8, Vehicle range with varying A/C load

Differences in accessory load have a far greater impact on vehicle energy consumption and range. The peak air-conditioning load of 3000 W reduces EV range over the SC03 drive cycle by 36%. An A/C load in the 1000 W to 2000 W range represents the power required to maintain conditions once “pull-down” is achieved. Applying advanced glazing, using solar powered ventilation on parked vehicles, and better recirculation strategies or localized A/C for the occupants might achieve similar reductions in A/C load. Nonetheless, a 20% reduction in range can be expected in most situations, shown in Table 6-6.

6.4. Drive schedules for fuel economy testing

Upcoming vehicular fuel economy rating methods and tail pipe emissions standards (2011-2014 phase-in) are set under the U.S Environmental Protection Agency (EPA). They generally carry into Canada unchanged. These standard drive schedules represent typical city, highway, and aggressive driving patterns.

Table 6-7, EPA standard drive schedules in use

Drive cycle	**Distance,** km	**Top speed,** km/h	**Average speed,** km/h	**Accessory load,** W
UDDS	12.07	91.2	31.5	500
HWFET	16.45	96.4	77.7	500
US06	12.8	129.2	77.2	500
SC03	5.8	88.2	34.8	3500

Drive schedules were first introduced in 1975. They serve as a basis for comparing fuel economy of vehicles with different size and weight classes originating from various manufacturers. Over the years, adjustments and weighting factors have been adopted to reflect the real world consumption due to the changes in speed limits and driving habits. Starting in 1984, City and Highway fuel economy from lab tests were adjusted downwards by 10 and 22 percent respectively in the U.S (10 and 15 percent in Canada), to better represent the real world fuel economy values being achieved by consumers, although the estimates were still optimistic. Until 2008, all “EPA Label” fuel economy values were based on variations in computing results based on the UDDS and HWFET schedules. These schedules remain unchanged even today, however supplemental drive schedules have been added to the existing ones (US06 and SC03) and are under a mandatory phase-in period (2011-2014) [US Federal Register 2007].

The US06 drive cycle was introduced as a supplemental cycle for high speed and aggressive driving. SC03 was introduced for testing fuel economy with an air-conditioning load. The standard “Combined Cycle” derives fuel economy by taking an average of 55 percent city (UDDS) and 45 percent highway (HWFET) fuel consumption. This weighting factor was altered to 43/57 (city/highway) starting Model Year 2005 to better reflect real-world driving patterns. These lab-tested numbers were then adjusted again before being presented to consumers. Canada uses 10% / 15% (city/highway) adjustment factors to further correct the lab-tested data, while the US uses 10%/ 22% (city/highway) [Khanna 2009]. For 2005 and later model years, the adjusted composite fuel economy values for cars and trucks combined were approximately 6% lower than the earlier composite fuel economy values.

The purposes of adding the US06 and SC03 driving cycles, and incorporating weighting factors is to make vehicle fuel economy estimates on the EPA label more realistic. To further improve this accuracy, starting 2010, vehicle manufacturers need to generate vehicle specific 5-cycle drive schedule fuel economy figures. This new schedule is composed of City, Highway, US06, SC03 and cold start City Cycles, with different weighting factors assigned to each.

Table 6-8, Effect of 5-cycle tests on EPA city and highway fuel economy label [EPA 2007]

	City			Highway			Combined*		
	Current (mpg)	5-Cycle (mpg)	Percent change (percent)	Current (mpg)	5-Cycle (mpg)	Percent change (percent)	Current (mpg)	5-Cycle (mpg)	Percent change (percent)
Hybrids	42.7	33.0	−22.3	42.8	36.9	−12.9	42.6	35.0	−17.1
Diesel (1 vehicle)	26.2	23.4	−10.7	35.3	32.0	−9.3	29.6	27.6	−6.7
Conventional Vehicles									
12 Highest FE	30.9	26.9	−12.9	36.6	34.0	−6.9	33.2	30.5	−8.0
12 Lowest FE	10.2	9.5	−6.9	14.8	14.8	−0.2	11.9	11.9	0.4
Average	18.6	16.5	−10.8	24.6	22.8	−7.4	20.9	19.6	−6.0

Table 6-9, EV 5-cycle fuel economy, PSAT simulated results

	City, MPGGE			**Highway,** MPGGE			**Combined,** MPGGE		
	Current, unadjusted	**5 cycle**	**Percent change**	**Current, unadjusted**	**5 cycle**	**Percent change**	**Current, unadjusted**	**5 cycle**	**Percent change**
EV	108	95	-12%	89	81	-9%	97	87	-10%

Use of the 5-cycle test will reduce current city and highway fuel economy label values further. The strongest influence of this change reflects on hybrids, as shown in Table 6-8. A 5-cycle simulation was run on the Electric Saturn Vue conversion from previous examples revealing a 10.3% reduction, intermediate between fleet average and hybrid architectures, shown in Table 6-9. The energy use numbers reflect the vehicle's plug-to-wheel (PTW) consumption.

The Electric Saturn Vue is evidently capable of completing all EPA standard drive cycles, while satisfying reasonable consumer performance expectations. Affordability concerns are addressed in Section 7. Consumer convenience is mainly associated with recharging time and range. Currently, EV charging is performed at three voltage and current levels, commonly referred as Level 1, 2 and 3 charging [NEC Handbook 1999]. Table 6-10 summarizes the maximum electrical specifications of the three charging levels.

Table 6-10, Charging level specifications [SAE J1772 2010]

	Voltage (VAC)	**Current (Amps)**	**Power (kVA)**	**Frequency (Hz)**	**Phase**	**Standard Outlet**
Level 1	120	12	1.44	60	single	NEMA 5-20
Level 2	208/240	80	16.6/19.2	60	single	SAE J1772
Level 3	480	400	192	60	three	N/A

Level 1 charging normally requires 8 to 14 hours to fully charge a vehicle, depending on battery pack capacity. There is no immediate need for upgrades to the present electrical infrastructure for this charging level; however it could benefit from a "Smart Grid". The obvious disadvantage is the lengthy charging time, inconvenient for longer trips, and only suitable for overnight charging. It is meant for PHEV with small battery packs. Level 2 charging can be done in 4 to 6 hours, but requires additional features include grounding and electrical isolation, personnel protection from shock, a no-load interlock, and a safety breakaway for the cable and connector [Pacific Gas and Electric Company 1999]. Level 3, also known as “DC fast charging”, requires high levels of voltage and 3 phase grid current to replenish the bulk of an EV’s battery capacity in as little as 10 to 20 minutes. Here charge rate is at the battery’s thermal limit.

For electric vehicles to roll out successfully, Level 3 charging stations need to be in place to minimize driving and refueling habit alterations. Such change is hard to promote and could be a major resistance against EVs. Recently the standard defining available power from a Level 2 system has been updated from 32 A at 240 V to 80 A at 240 V. Level 2 and Level 3 charging systems can be acquired and installed for an estimated $2,000 - $4,200 and $110,000 - $160,000 for personal and commercial uses, respectively. Gas stations cost about $2 million each to build [AeroVironment 2009]. Such systems are the most feasible solution economically and technologically. Both Level 2 and Level 3 charging systems have been available since the late 90’s [Pacific Gas and Electric Company 1999], and are on a resurgence today.

7. Electric Vehicle Cost Assessment

Electric vehicles were re-introduced in the 90's to reduce petroleum reliance and tailpipe emissions. However, the commercialization process wasn't a success as intended. Since its invention, the electric vehicle has never dominated the market except in the very early days (1900-1920). The barrier has always been its energy storage system. The energy density of any battery chemistry is far less than that of petroleum fuel used on conventional vehicles. Recent battery technology advancement has made electric vehicles more comparable to conventional vehicles in performance, while the cost of advanced batteries still shadows their potential for commercialization. Newer batteries have shown their effectiveness in hybrid electric vehicle applications with the success of generations of HEVs such as the Toyota Prius and Ford Escape Hybrid, both employing nickel metal hydride batteries. As major auto manufacturers are announcing that their next generation of HEV, PHEV and EV's will be powered by lithium-ion batteries, these have become a default industry standard for advanced technology vehicles. While overall safety is still a lingering concern, this section will focus discussion on a cost assessment of battery electric vehicles.

7.1. Cost related Parameters

The viability of an electric vehicle is closely related to five battery characteristics, commonly known as the "5C", Capacity, C-rate (charge/discharge rate), Cost, Cyclic life and Calendar life. Out of these five, Cost, Cyclic life and Calendar life varies the most between manufacturers and their technologies, whereas capacity and C-rate is finalized by adjustments at production. Unlike lead acid or nickel metal hydride batteries, terminology which specifies the battery chemistry, lithium-ion represents a family of battery chemistries. Among them, very different characteristics are demonstrated, which adds to the complexity of cost models for electric vehicles. Battery capacity and C-rate translates to energy and power density of the cell, respectively. Energy density (by mass and by volume) is directly proportional to vehicle range, and power density determines a vehicle's dynamic performance. For electric vehicles, it is most important to have an energy dense battery pack, since it is the only energy source. Limited travel range is a known practical constraint for electric vehicles from the past. Power density is less of a concern for the EV (as opposed to the hybrid) as it is already compensated for by a larger pack. Research has shown that the energy density of a lithium-ion battery can surpass 350 Wh/kg (demonstrated by lithium sulfur cells), significantly higher than what is currently on the market, ≈180 Wh/kg. The economic link between these high performance cells and the overall cost is yet unknown but shows potential because they employ low cost materials.

Cyclic and calendar life have a less obvious relationship to the vehicle's performance because advanced battery chemistry doesn't exhibit problems when purchased new or when lightly used. Lifetime factors are significantly affected by how batteries are stored or used, which is always an unknown factor at the consumer level, and invokes warranty concerns for manufacturers. The state of health of a battery is difficult to access by vehicle operators at any instance, as it is a function of day-to-day storage and application conditions. One parameter universal to degradation in battery performance is the internal resistance rise of cells, common for all battery chemistries.

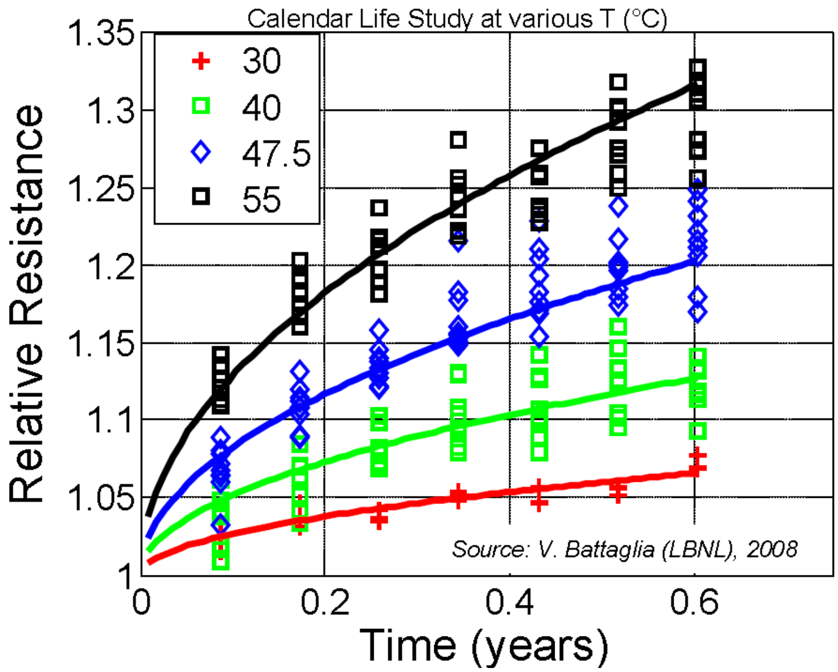

Figure 7-1, Battery Calendar Life Study at various temperatures [Pesaran 2009]

The internal resistance can be affected by many factors, including operating temperature (Figure 7-1), storage temperature (Figure 7-2 and 7-3), and depth-of-discharge (Figure 7-4). As Figure 7-5 is based on data circa 2003, the general consensus now is that Li-ion technology equates or surpasses NiMH in cycles vs. DOD [CARB, 2007].

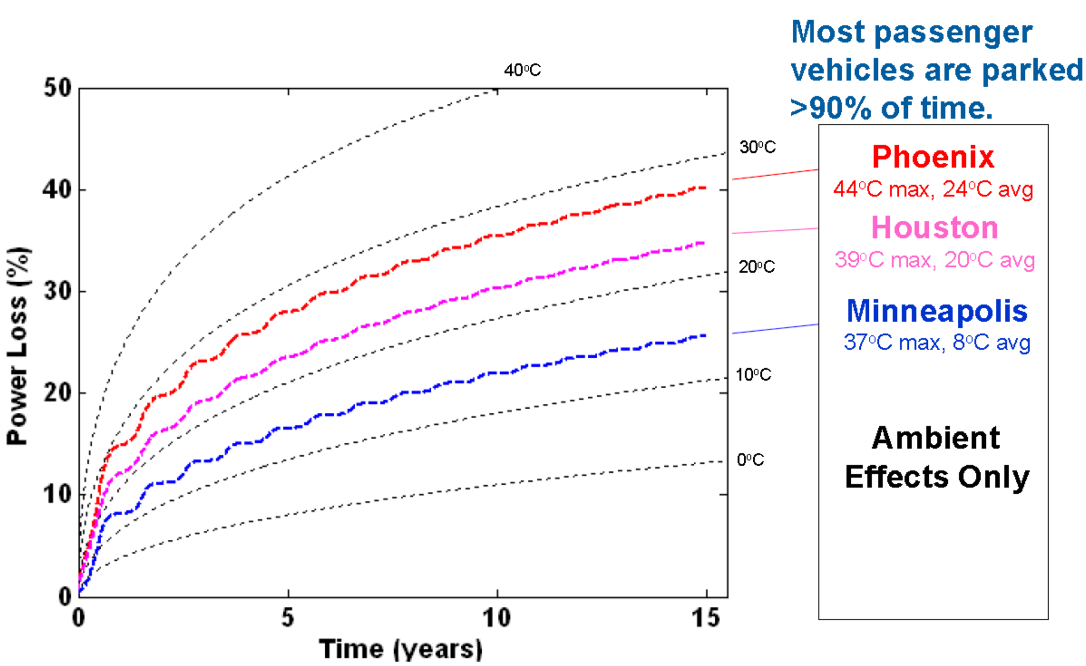

Figure 7-2, Ambient condition influences on battery [Pesaran 2009]

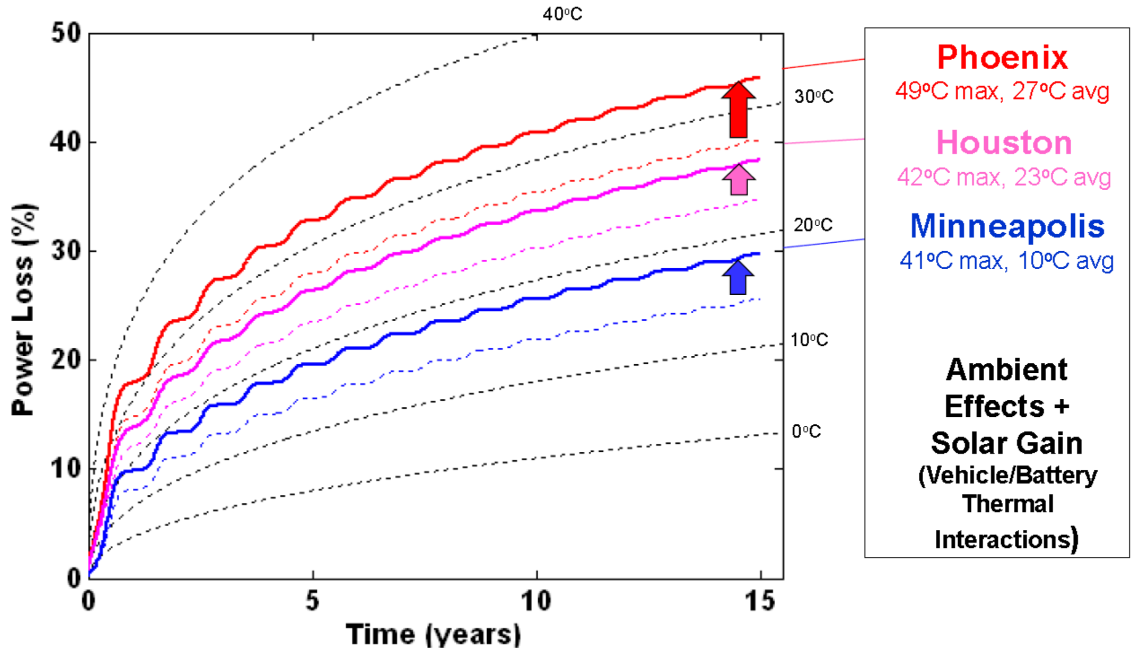

Figure 7-3, Ambient condition + Solar gain [Pesaran 2009]

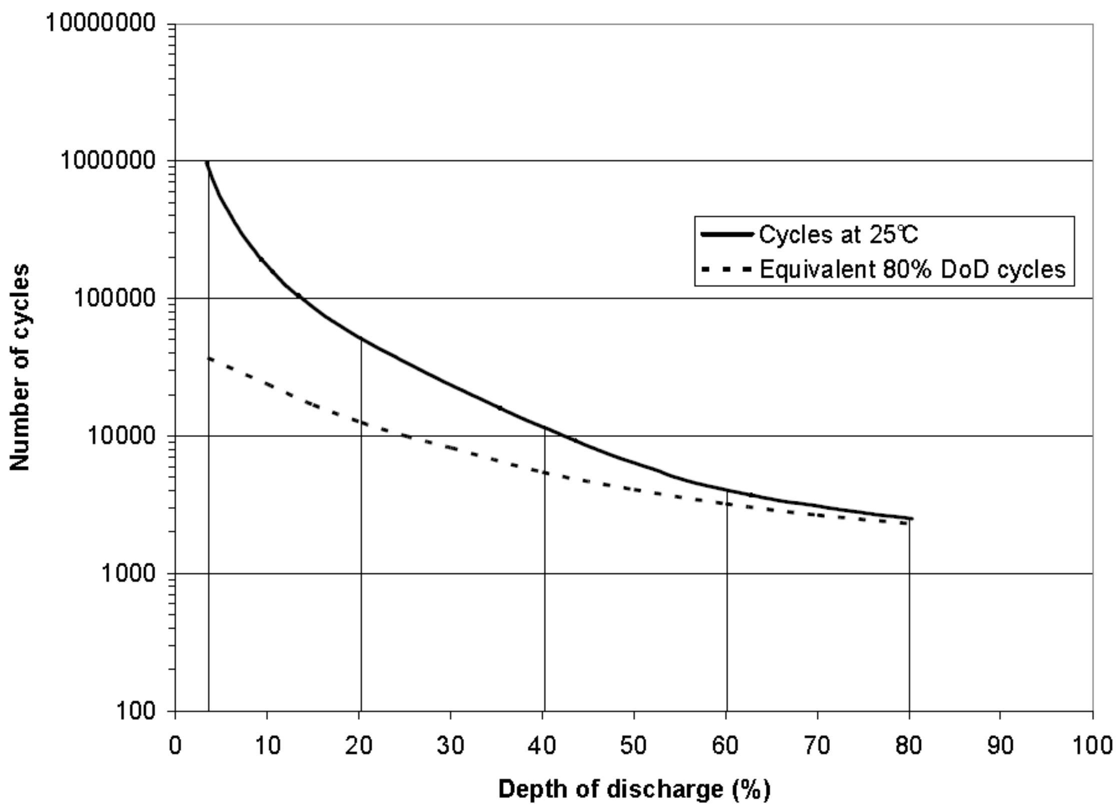

Figure 7-4, Battery Cyclic Life Study at various DOD [Kalhammer 2007]

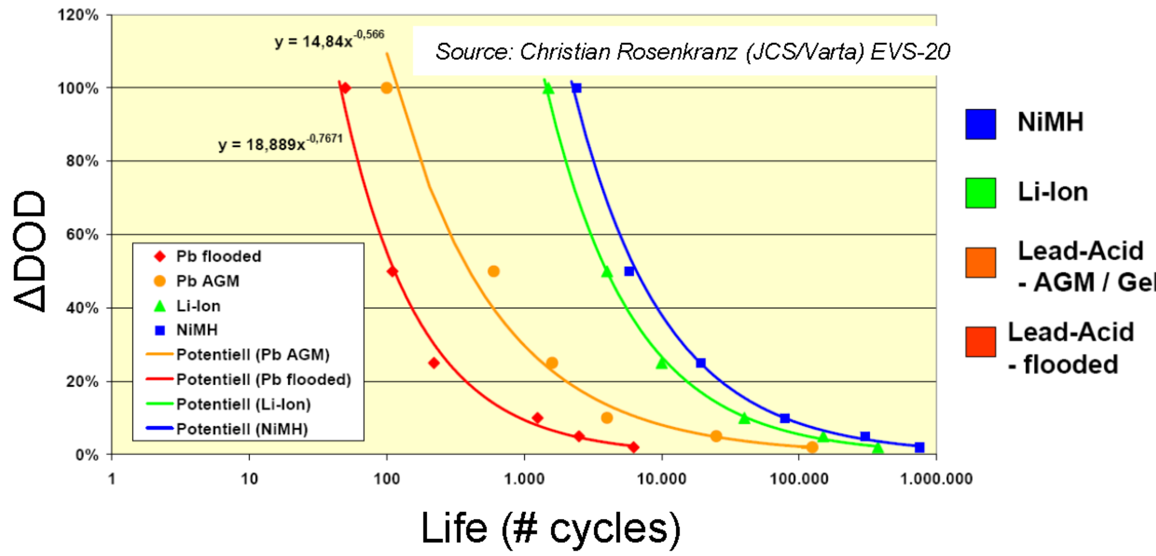

Figure 7-5, Battery Cyclic Life Study at various DOD [Pesaran 2009]

Ultimately, batteries are expected to last the lifetime of a vehicle, generally accepted to be fifteen years at 20,000 km per year for conventional vehicles. For the commercialization of electric vehicle to be successful, this should be the baseline expectation for EVs as well.

The United States Advanced Battery Consortium (USABC), formed by GM, Ford and Chrysler, has outlined price goals for advanced batteries in EVs to be $100/kWh in the long term and $150/kWh as a minimum goal for commercialization. Today this price is $450/kWh for large supply contracts [Deutsche Bank 2010]. However, it is generally believed that lithium-ion batteries have significant potential to achieve such cost reduction, on the basis of production scales expected in the next years. Unlike the NiMH battery, its production level has never met the commercialization requirement.

The cost of a lithium battery may be reduced by lower raw material cost, increase packaging efficiencies, higher energy density (uses less material), and increased production volumes. Comprehensive studies on advanced automotive battery costs were conducted by the CARB Battery Technology Advisory Panel and Argonne National

Laboratory. Good prospects for cost reduction of lithium-ion batteries exist, shown in Figure 7-6.

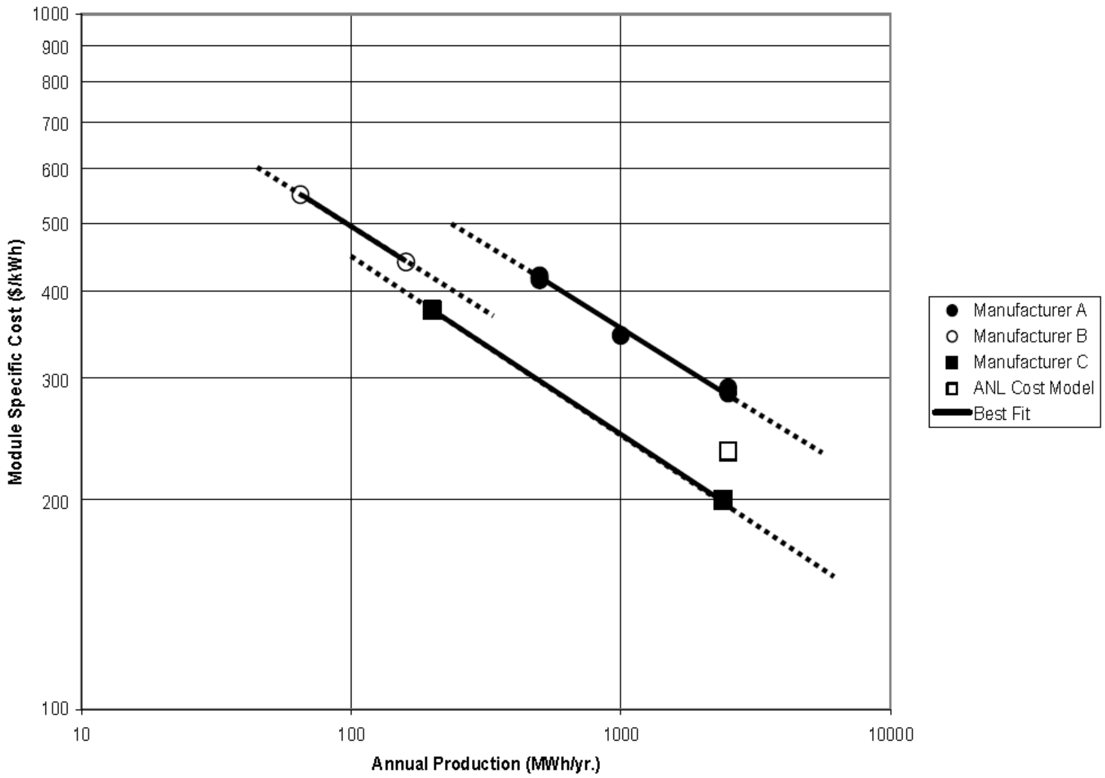

Figure 7-6, Lithium-ion module specific cost projection [Kalhammer 2007]

Lithium-ion batteries exist in different form factors, cylindrical, prismatic and pouch. While manufacturing processes for respective form factors are similar among suppliers, prismatic and pouch cells are more popular for automotive application. This is due mainly to superior energy density of these formats coupled with the packaging constraints on a vehicle. The price difference at the manufacturing level is caused by battery chemistries and production volumes.

7.2. Battery Pack Cost Breakdown

Research has been conducted to determine the cost of batteries at different levels, Table 7-1.

Table 7-1, Cost of High Energy Li-ion batteries in \$/kWh (from year 2000 data) [Anderson 2009]

Level of Integration	Cost Category			Total (\$/kWh)
	Materials	Manufacturing	Other	
Cell	734.53	23.15	86.90	**844.59**
Module	771.79	26.77	86.90	**885.47**
Pack	864.38	31.68	230.27	**1126.33**

Cost is broken down to cell, module and pack level. As expected, material costs dominate the total at all levels, a detailed breakdown is shown in Figure 7-7.

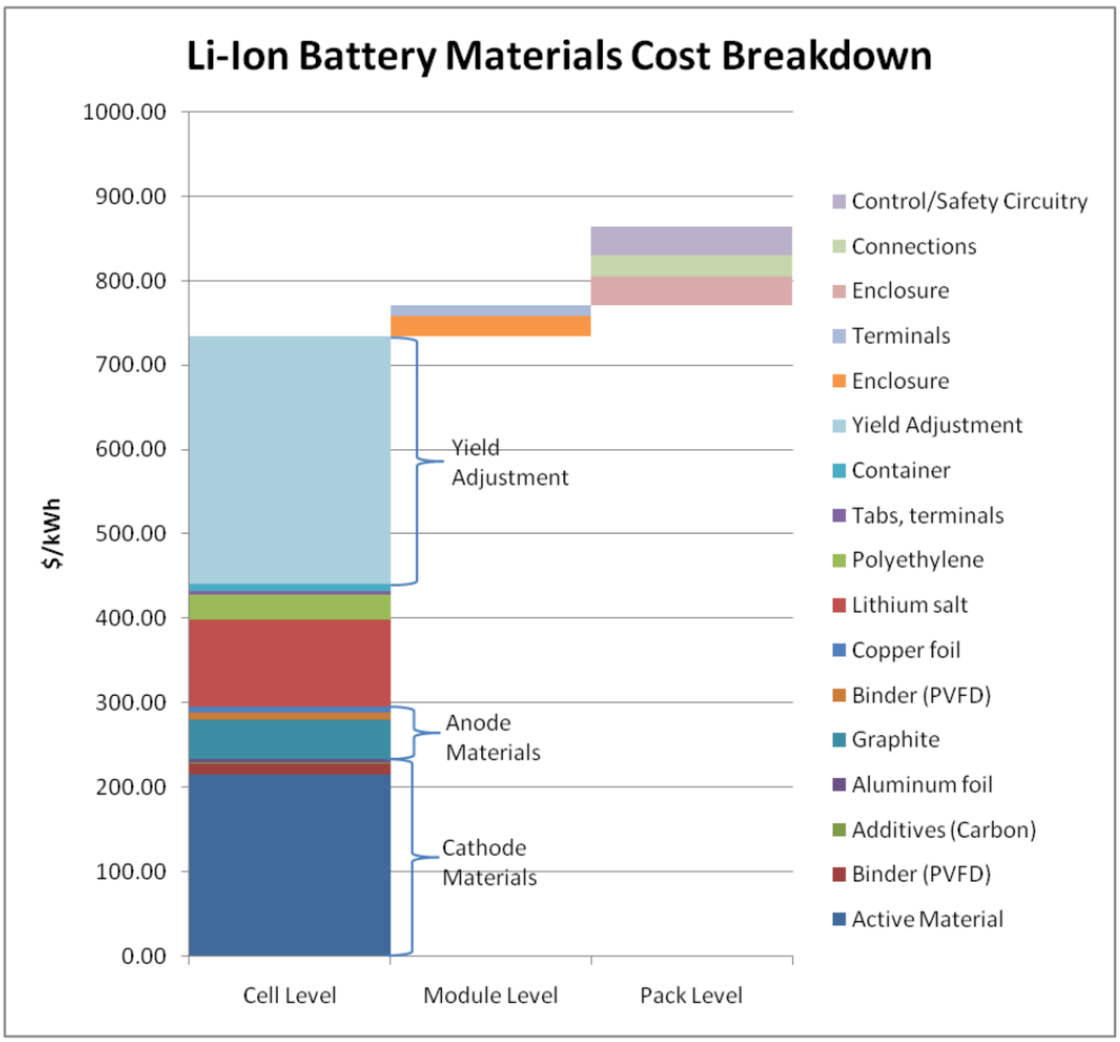

Figure 7-7, Material cost breakdown for Li-ion batteries [Anderson 2009]

"Yield Adjustment" dominates the material cost at the cell level. This is a result of tight quality requirements set by the automotive industry. All cells that fail to meet the requirements contribute to this cost increase. The manufacturing yield was assumed to be 60% during the early development period, since exact data was kept confidential by manufacturers in these studies. It is suspected that "yield adjustment" also contains a profit margin [Anderson 2009]. Cathode material cost follows closely in second place. This cost is reduced by switching to more commonly found materials, such as iron phosphate, sulfur, or inexpensive metal oxides, rather than first generation chemistries that relied on cobalt. There are also rising concern regarding the known world supply of lithium when mass production of PHEVs and BEVs start in the next decade if current production of 60 million vehicles per year would be replaced with highly electrified vehicles [Tahil 2006]. However, this level of mass production is not likely to be achieved by the automakers with the cost of lithium-based cells and battery packs today.

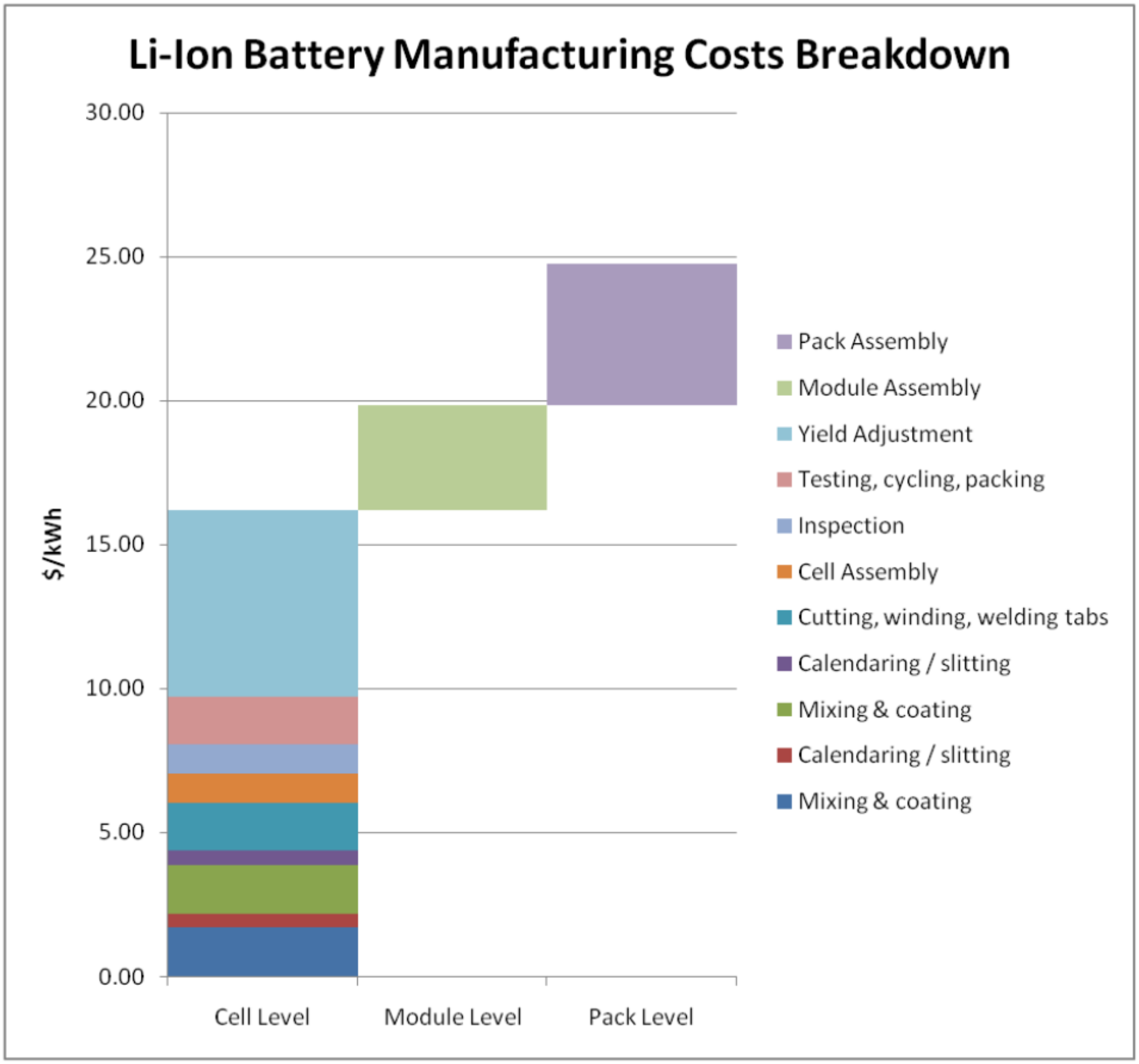

Figure 7-8, Manufacturing cost breakdown for Li-ion batteries [Anderson 2009]

Figure 7-8 shows the manufacturing breakdown, which exhibits similar cost distribution trends: yield adjustment dominates the total cost. Again, these factors are closely related to production volumes.

Data on consumer cells has shown that cell prices have dropped steadily for lithium-ion batteries since their invention while energy and power density continuously shows improvement (Figure 7-9). However, the rate of improvement has been slowing down for the past decade.

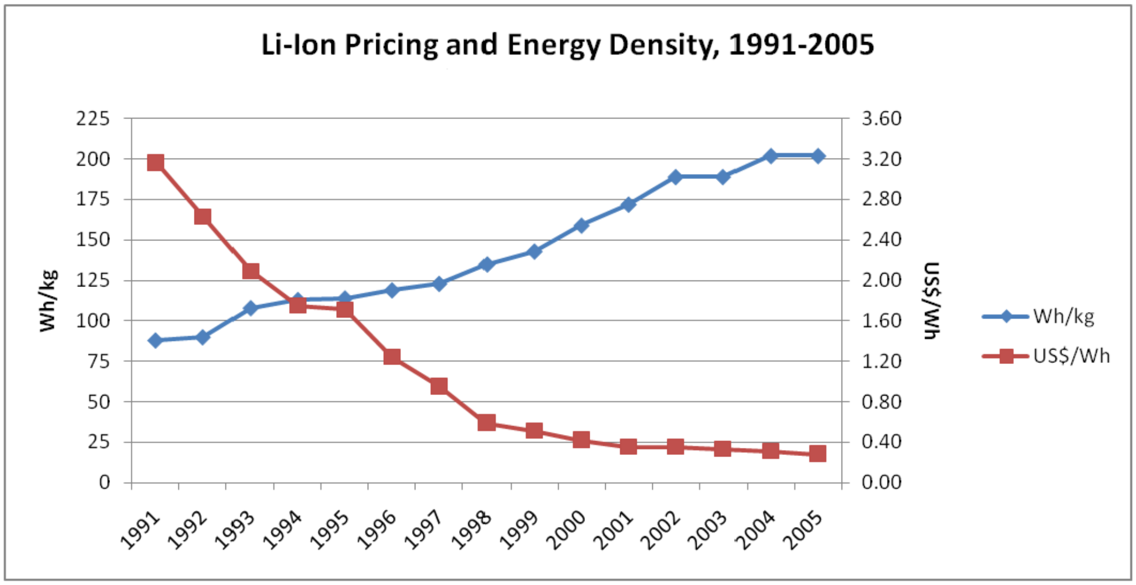

Figure 7-9, Historical trend of Li-ion batteries [Anderson 2009]

This reduction in price is due to production increases and lowed carbon and material cost in countries like China. Diminishing rates of cost reduction suggests that, in the future, a strong increase in production coupled with chemistries that make better use of base materials may be the only stimulus to further decrease cost. This can be achieved if the market adapts to electric vehicles. For consumers to accept such change in technology, electric vehicles need to show capabilities similar to that of conventional vehicles. Therefore, technology advancement also has to coordinate with consumer awareness of the advantages and limitations, in order to fully utilize the capabilities of electric vehicles. As previously mentioned, battery cyclic and calendar life varies at the vehicle level. Since small SUVs and modern compact crossover vehicles dominate the light-duty market, the following cost analysis was done with reference to such vehicle platforms.

Table 7-2, Baseline parameters of a compact crossover

Parameter	Mass	Frontal Area	Drag Coefficient	Passenger Capacity	Targeted Range
Unit	*kg*	m^2			*km/mile*
	2130	2.641	0.376	5	321/200

For a typical driving pattern in the suburbs, a minimum drive range of 321 km (200 mile) per charge cycle is used for a highway-capable full function electric vehicle. This is the same target as set for fuel cell vehicles by the California Air Resources Board (CARB). In a worst case scenario, assuming a daily traveling range of 320km, 5 days per week, or an annual 83,000 km; this results in 260 full charge/discharge cycles per year for the battery pack. For a pack exhibiting 1300 cycles before reaching 20% degradation in capacity, a pack replacement might be required in 5 years. This still translates into an increased operating cost as compared to a conventional vehicle. In reality, 78% of North American drivers travel less than 40 miles per day, therefore only one complete charge/discharge cycle might be performed every week (under the assumption that charging is initiated on a depleted pack). The battery pack should then last up to 19 years. Conventional vehicle are engineered to last ≈15 years at an average driving range of 20,000 km per year. Electric vehicle battery technology today appears sufficient for light-duty vehicle applications. As shown in Figure 7-4, cyclic life shows an exponential growth with decrease in depth-of-discharge, which means that if vehicle were more frequently charged after use, the battery pack would sustain more charge/discharge cycle before exhibiting a 20% degradation in capacity (20% capacity degradation is an industry standard for evaluating performance). Further, the total energy throughput rises about 40%

as depth of discharge is reduced to lower levels. Following this trend, the battery pack on a full function electric vehicle could easily outlast the vehicle, calendar life permitting.

The cost of the battery pack is still the biggest barrier for commercialization. Increasingly heightened capital investment is required in the order of HEV, PHEV and EV; in spite of the lowered operating costs. With rising petroleum prices, the advantage of lower operating costs will become more significant. These are prime driving factors for the introduction of electric vehicles in schemes like "Project Better Place" for various locations around the world where fuel and vehicle tariffs predominate [Deutsche Bank 2010].

The USABC long term battery goal for commercialization of electric vehicles is summarized in Table 7-3. All minimum technical goals on battery performance are currently being achieved, however, the targets on battery price are still too optimistic. Electric vehicles will however become more economically viable with rising fuel prices. Other means of promoting electric vehicles and similar fuel efficient plug-in alternatives can be executed through change of government policy, such as the introduction of incentives to purchase or rebates. However, these exercises tend to be short lived. Mass acceptance depends on overall consumer economics. The particular case of the European Union is perhaps a better case for study, where fuel cost is three times the North American level. Here an economic case can be built on today's reality rather than outright speculation.

7.3. Vehicle Cost

While the battery technology advancement looks promising, its high cost remains a barrier to market-wide acceptance. The energy storage system contains more than just batteries, therefore the battery charger, battery HVAC system, packaging materials, and other electrification hardware must be included. Previous studies and OEM forecasts all conclude that EVs will cost significantly more initially than conventional vehicles in the near term. Since the late 90's, studies from US Department of Energy have suggested that on a life cycle basis, electric vehicle cost is not far from acceptable. However, with forecasted production cost reductions set by the manufacturers, electric vehicles could soon show both technological and financial viability. Nissan for one appears to believe this and is tooling for 500,000 cars [Green Car Congress 2009].

The small volume pricing of a lithium polymer cell can be over $1000/kWh, while the OEM price at mass production volumes can be under half of this value today. Since the size of a battery pack decides the vehicle range, early electric vehicles with advanced batteries will likely be compact sedans; for their low curb weight makes them more energy efficient per km. Given a practical range, taken as of 200 miles per charge cycle, batteries alone for such a vehicle could cost more than $15,000. With 80% DOD, lithium polymer batteries have shown the potential to last more than 1500 cycles, which translates into the lifetime mileage of the hypothetical electric vehicle. For a conventional vehicle with a design life of 300,000 km, and typical gasoline ICE fuel economy of 8 L/100km, the life time fuel cost with an average fuel price of $2/liter is $48,000. The life time energy cost for an electric vehicle with similar usage would be $5,400, assuming electricity at $0.10/kWh. An electric vehicle has fewer rotational components compared to conventional vehicles, thus a reduction in the operating and maintenance cost of EVs. Petroleum prices are predicted to rise more rapidly in the future, therefore the capital investment in an electric vehicle has the potential to break even much sooner than previously expected.

Another factor affecting the length of the break even period is the vehicle driving cycle. EVs are less suited to aggressive highway driving usage, and high accessory loads as A/C. Their niche appears to be urban and suburban usage.

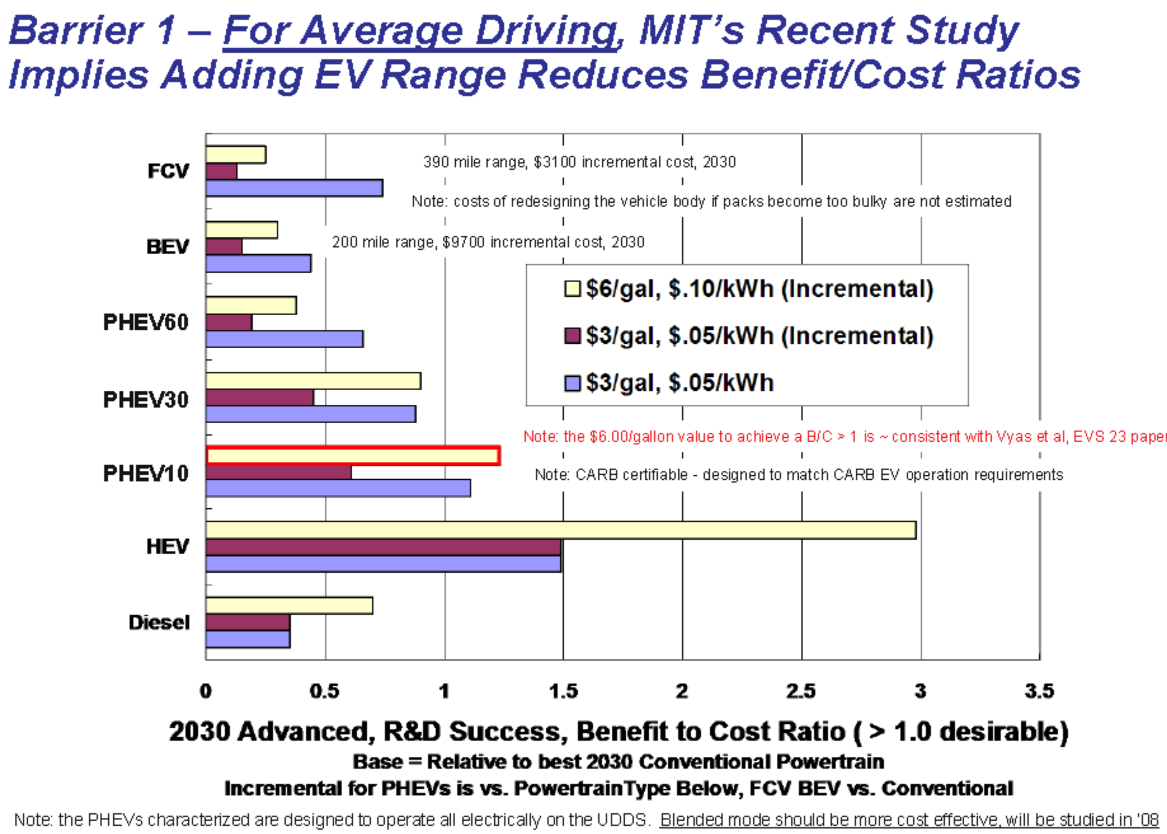

Figure 7-10, EV Commercialization Barrier: reduced range [Santini 2008]

Studies have shown that incremental cost/benefit ratios suffer with increased electrification, Figure 7-10; however the inverse is true in terms of petroleum energy use and GHG emissions. Figure 7-11 indicates that in order to meet 80% CO_2 emissions reduction targets as proposed by CARB there appears to be no choice other than EVs and FCVs [McCarthy 2009].

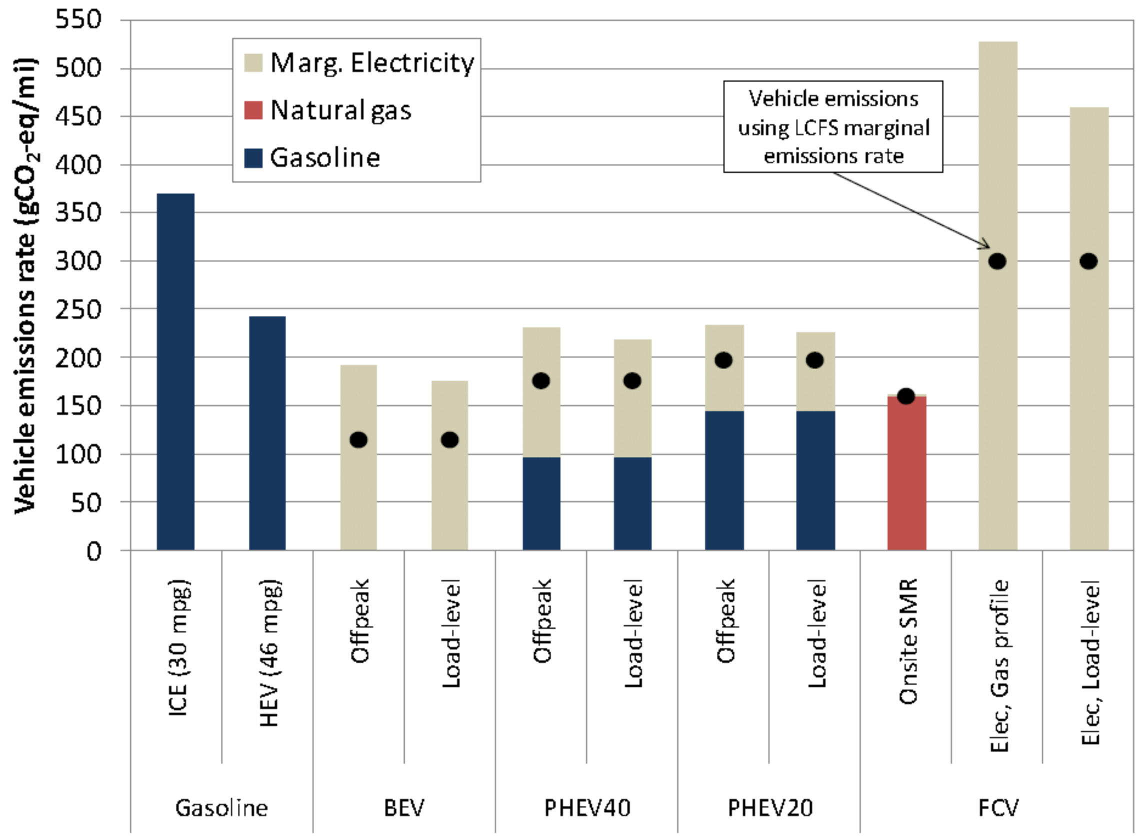

Figure 7-11, Well-to-wheels vehicle GHG emissions rates by energy source, based on marginal electricity mixes from EDGE-CA simulations for 2010 (median hydro availability). [McCarthy 2009]

Here electricity generation emissions are plotted for California, the black dots representing CO_2 rates corresponding to their low carbon fuel standard. By comparison the average Canadian rate is approximately 45g CO_2 / km using 190 Wh/km well-to-wheel as for the BEV in the California study (208 g CO_2 / kWh from Canadian average electricity production while the USA average emissions are 625 g CO_2 / kWh) [NRCAN Office of Energy Efficiency].

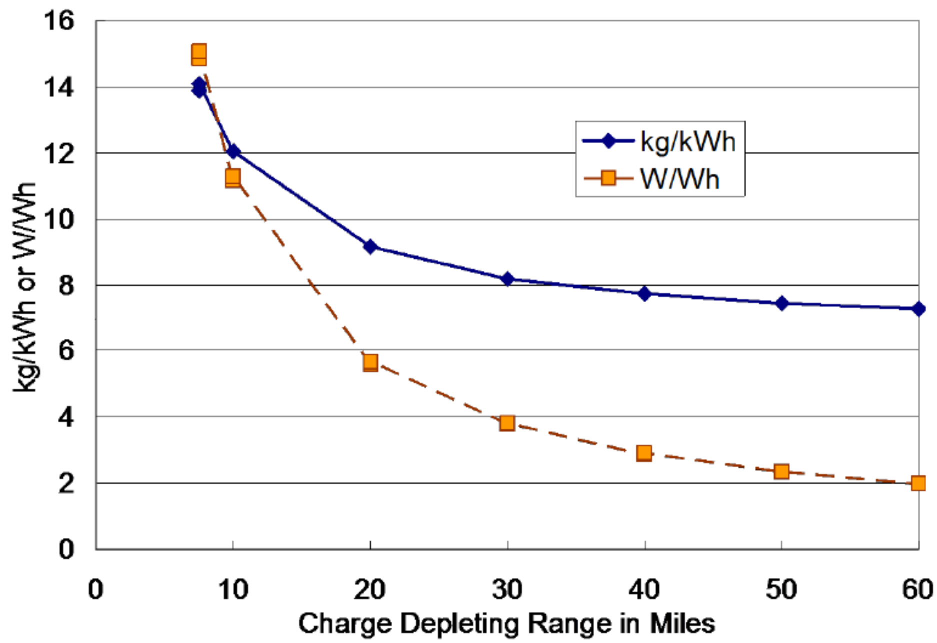

Figure 7-12, PHEV Commercialization effect of lower power to energy ratio [Santini 2008]

Short range electric vehicles, PHEV-10 or PHEV-20 require high power batteries which compromises energy density, hence battery cost per km of charge depleting range reduces with larger battery packs. However if the pack is oversized and overweight, consequently increasing energy consumption per km, then capital costs become excessive. It appears that currently manufacturers are targeting 100 mile range for BEVs as the best benefit/cost ratio [Nissan Leaf, Mitsubishi i-MiEV, Ford Focus EV, and GM Volt full electric version]. With development of advanced lithium battery technology (i.e. lithium sulfur) battery energy density can exceeds 400 Wh/kg [Sion Power]. Because electric vehicles require energy cells as opposed to power cells, a lower W/Wh ratio can be employed. Assuming constant per kg material costs, there is potential to cut costs by a factor of 2 with these higher energy cells while increasing range due to reduced weight.

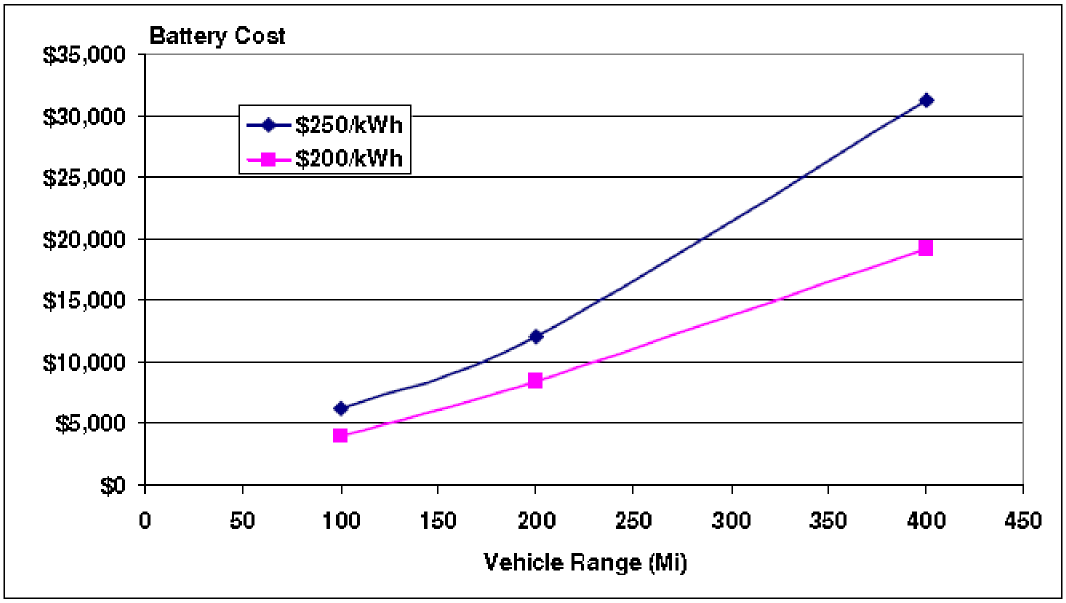

Figure 7-13, Battery Cost vs. Vehicle Range [Kromer 2007]

According to current California Exhaust Emission Standard regulations, for zero-emission vehicles to qualify as a full function electric vehicle, the vehicle has to have a minimum range of 100 miles with a fully charged pack [CARB 2003]. No doubt the CARB ZEV credits and Federal tax rebates ($7,500) are swaying technical decisions. In recent years, a driving range of 200 miles was set for fuel cell vehicles. In this case, the lack of refueling infrastructure dictates a higher minimum range requirement, whereas most charging for electric vehicles is expected to take place during off-peak period (at night) and at home. Nonetheless, a desired range for electric vehicles in the 200-300 mile range would entail few compromises for consumers. EV capital and life cycle cost are summarized in Table 7-4 and 7-5; and presented in Figure 7-14 and 7-15. Government incentives are not included when computing total EV capital cost since these policies are put in place at the initial stage of commercialization and are not meant to reflect the cost of EVs to manufacturers.

Table 7-3, Battery cost assumption for cost models

Year	Battery Cost, $/kWh
2009	750
2010	500
2020	350
2030	150

Table 7-4, EV Capital Cost

				Production Volume											
				2009			2010			2020			2030		
Vehicle Class	**Range,** mile	**Pack size,** kWh	**Energy Consumption,** Wh/km	>5k/year			>50k/year			>80k/year			>120k/year		
				Battery pack, $	Increment, $	Total, $	Battery pack, $	Increment, $	Total, $	Battery pack, $	Increment, $	Total, $	Battery pack, $	Increment, $	Total, $
Compact EV	100	25	155	18750	29000	45000	12500	19000	35000	8750	12200	25000	3750	4760	15000
Mid-size EV	200	60	186	45000	35400	57400	30000	28000	50000	21000	17400	35000	9000	7920	22000

Table 7-5, EV Life Cycle Cost

			2009				2010				2020				2030			
Vehicle Class	**Range,** mile	**Pack size,** kWh	**Gas** $/liter	**Ele.** $/kWh	**Increment,** $	**Breakeven period,** yr	**Gas** $/liter	**Ele.** $/kWh	**Increment,** $	**Breakeven period,** yr	**Gas** $/liter	**Ele.** $/kWh	**Increment,** $	**Breakeven period,** yr	**Gas** $/liter	**Ele.** $/kWh	**Increment,** $	**Breakeven period,** yr
Compact EV	100	25	0.66	0.11	29000	43	0.79	0.12	19000	23	1.32	0.16	12200	8	2.64	0.2	4760	1.5
Mid-size EV	200	60	0.66	0.11	35400	45	0.79	0.12	28000	29	1.32	0.16	17400	10	2.64	0.2	7920	2

*Fuel and electricity price is projected using historical record from US Department of Energy, Figure 7-16 and 7-17.

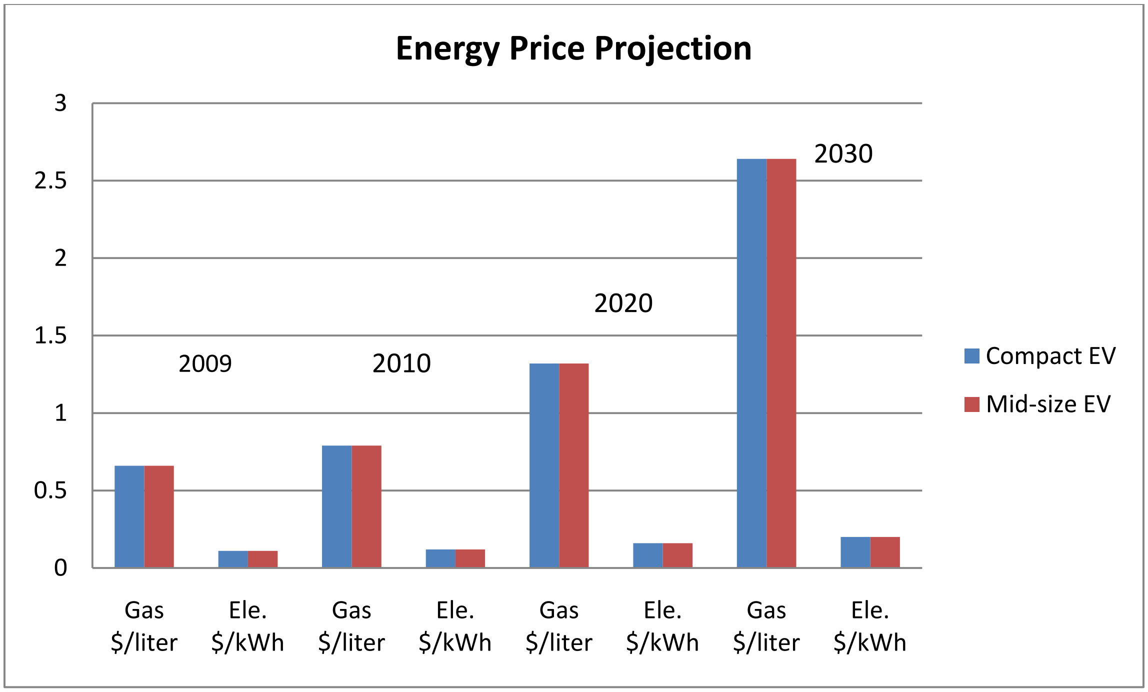

Figure 7-14, Energy Price Projection [US DOE]

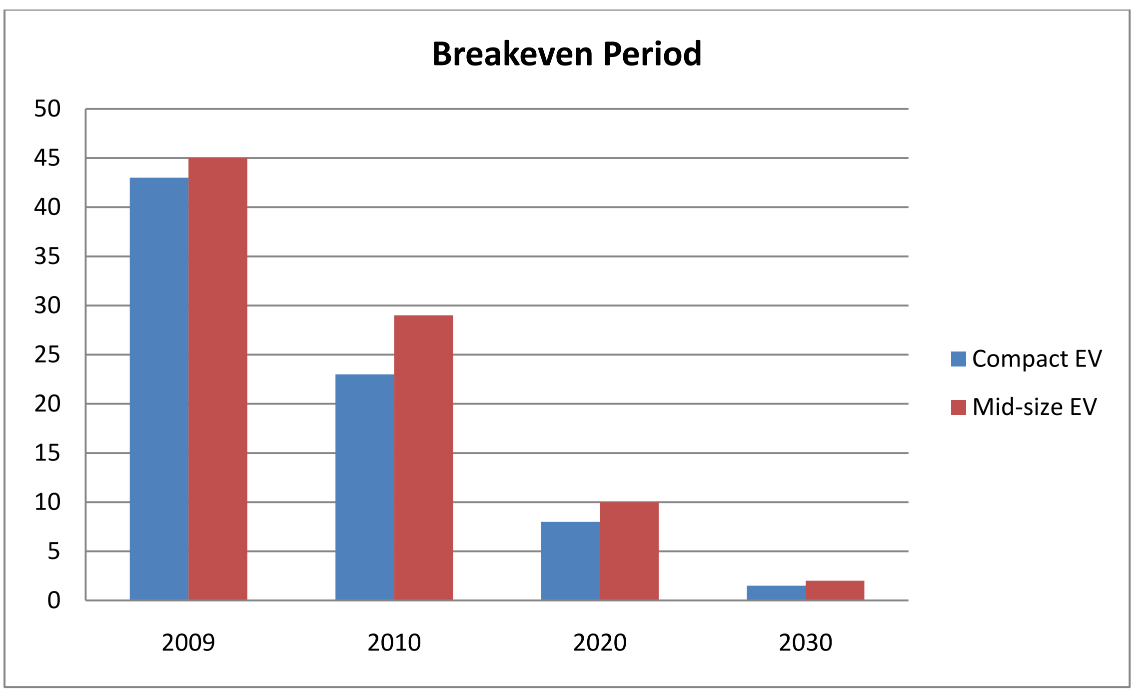

Figure 7-15, Breakeven Period of Compact and Mid-size EV

Table 7-6, Scaling Factors for Li-ion Technology Specific Costs [Kalhammer 2007]

Battery Size, kWh	**Cell → Module**	**Module → Battery Pack**	**Cell → Battery Pack**
40-45	1.03	1.2	1.24
20-25	1.04	1.25	1.3
12-15	1.05	1.33	1.4
7	1.07	1.42	1.52
2	1.1	1.5	1.65

Cell volumetric energy density is compromised when packaged. Battery packaging factors are listed in Table 7-6. The trend shows that packaging factor (volumetric energy density loss) decreases as the battery size increases since certain energy storage system components are common in all battery packs.

Because conventional vehicle prices haven't seen significant change over the past decade (inflation included), for cost modeling this price is kept unchanged. Gasoline and electricity prices for the above model were projected from US Department of Energy historical data, as plotted in Figure 7-16 and 7-17. This is a more conservative forecast compared to the European projection.

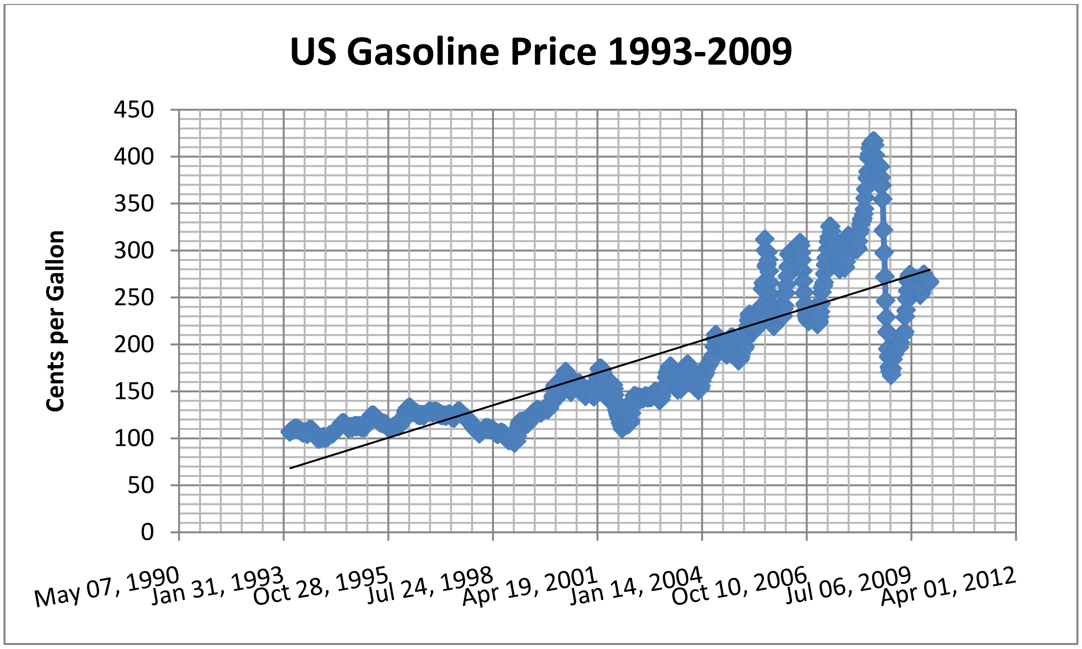

Figure 7-16, US Gasoline Price Trend [US DOE]

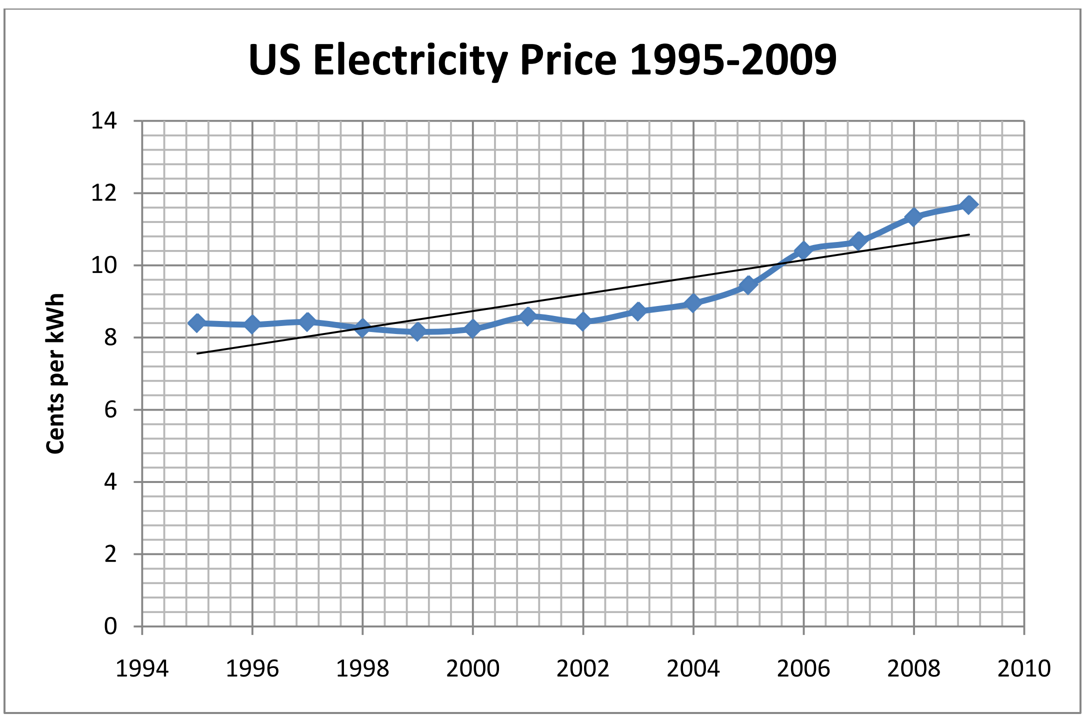

Figure 7-17, US Electricity Price Trend [US DOE]

Current battery cost, even at the OEM level is still far from the USABC long-term goal of $100/kWh, Table 7-7. Consequently this makes a 100-mile capable EVs more financially feasible, with today's "at the pump" fuel prices, boosted by significant ($7,500) US government incentives. Fuel price is the main contributing factor, a fluctuation in prices can quickly shift consumer interests toward or away from electric vehicles. Possible taxes, tariffs and other additional costs levied on conventional vehicles were not included in the model. Such taxes are commonly known as "Carbon Tax", an environmental sur-tax on carbon dioxide emissions. This is presently being implemented in Australia, countries of the European Union, parts of the United States, and New Zealand; eventually these manifest themselves "at the pump". With the reduction of battery costs (several suppliers have announced increases of production worldwide) and rising fuel price and carbon taxes, EVs may soon be accepted into the mainstream automotive market. They are predicted to become sustainable in the economic sense over the next decade.

Laboratory experience suggests that batteries will last the life of the vehicle [Kokam 2008]; however the full effect of the combination of cyclic life and calendar life is still unknown. This presents a warranty risk currently built into the selling price. Concerns remain for the commercialization of electric vehicles, nonetheless the urge to reduce carbon dioxide emissions and oil dependence makes the electric vehicle the most "green" alternative that can be introduced at present. It can exist without the need for radical distribution infrastructure development and massive deployment investment as its nearest "green" competitor, the fuel cell vehicle.

Table 7-7, USABC goals for electric vehicle battery [USABC 2009]

Parameter(Units) of fully burdened system	Minimum Goals for Long Term Commercialization	Long Term Goal
Power Density(W/L)	460	600
Specific Power – Discharge, 80% DOD/30 sec(W/kg)	300	400
Specific Power - Regen, 20% DOD/10 secW/kg	150	200
Energy Density - C/3 Discharge Rate(Wh/L)	230	300
Specific Energy - C/3 Discharge Rate(Wh/kg)	150	200
Specific Power/Specific Energy Ratio	2:1	2:1
Total Pack Size(kWh)	40	40
Life(Years)	10	10
Cycle Life - 80% DOD (Cycles)	1,000	1,000
Power & Capacity Degradation(% of rated spec)	20	20
Selling Price - 25,000 units @ 40 kWh($/kWh)	<150	100
Operating Environment(°C)	-40 to +50 20% Performance Loss (10% Desired)	-40 to +85
Normal Recharge Time	6 hours (4 hours Desired)	3 to 6 hours
High Rate Charge	20-70% SOC in <30 minutes @ 150W/kg (<20min @ 270W/kg Desired)	40-80% SOC in15 minutes
Continuous discharge in 1 hour - No Failure(% of rated energy capacity)	75	75

8. Conclusion

Electric vehicles are considered alternative vehicle technology for future transportation, with doubts and concerns, yet they have been around since the invention of the automobile. EVs have the simplest of all powertrains. Electric motor technology is well established, with sufficient industrial and automotive application experience. A sensitivity study has been done to assess the effect of motor performance improvements on vehicles as a whole. Such improvement can only be marginal as electric machines are already very efficient; nonetheless through-put efficiency can be noticed in practice mostly as a function of off-peak performance characteristics.

Barriers to market penetration still lie with battery technology. Different battery chemistries were developed and tested under the original ZEV mandate. Questions about their safety, reliability, and longevity remain, even though older technologies are rapidly fading out and are being replaced by new lithium-ion chemistries. It has been a collective conclusion that the lithium based secondary battery is the choice of future alternative powertrain vehicles, including HEVs, PHEVs and EVs, due to its superior energy density and potentially lower lifecycle material cost.

Independent thermal cyclic aging tests on different lithium technologies with various cathode materials have been done by others. Results are promising, showing good tolerance to high discharge rate without absolute need for active cooling. Performance is expected to improve as the battery material chemistry advances. Manufacturing reliability depends largely on the processes used by individual manufacturers. Most claim that they have mass production capability and are improving production yield rates. Battery pack longevity and ultimately vehicle performance depends on cyclic and calendar life of the cells. This is a complex problem as it involves many dependent factors, such as DOD, C-rate, storage SOC, and temperature at charging/discharging. Combination effects of cyclic and calendar life become highly unpredictable as vehicle manufacturers still have limited accumulated road test data and market experience. At the battery manufacturer level, tests have consistently shown life exceeding 1000 cycles under 80% depth-of-discharge, and calendar life now reaching the 10-year minimum requirement by USABC.

Technologically, the battery is becoming ready for automotive applications. The last road block to commercialization is its high cost. Both battery suppliers and major auto manufacturers agree that full function electric vehicles are still far away from commercial viability, but recognize its potential of taking over significant market share. This market dominating process is expected to be slow. HEVs were introduced over a decade ago, yet only take up 2% of new vehicle sales [CARB Staff Assessment 2009]. At the current battery price of $750/kWh for small volume manufacturing and fuel prices below $3/US gallon, the operating cost reduction of a full function electric vehicle (highway capability and a minimum range of 320 km / 200 miles) will never be enough to compensate for the initial investment. Therefore, subcompact EVs will be introduced initially to reduce the incremental price jump in order to attract and encourage early adopters. According to fuel, electricity and battery price projections made, around year 2030 both the subcompact and mid-size electric vehicles become financially viable. Some studies concur with this finding, while others use a more conservative price projection for battery cost and performance, thus concluding that battery EVs will not be commercially successful [Greene 2010]. Government incentives are likely to be available for EV buyers as they have been for HEVs. However, these incentives are usually short-lived, as industry experts believe that the government policy needs to be "technology-neutral" [Anderman 2010].

A somewhat surprising finding of the present work is the ready technological feasibility of building electric vehicles with today's "off-the-shelf technology" that compare in range and "recharge times" to conventional fueled vehicles (400 km, <20 minutes). It is within the capacity of present battery and charger technology as being demonstrated by the UOIT EcoCAR project. So it is absolute cost rather than technology that limits introduction.

GHG emission reductions are one of the main driving forces behind EV development and market penetration. The BEV is a most promising option compared to other proposed solutions even when electricity production isn't at its cleanest. Electricity is the only potential energy source for transportation that addresses the need for fuel diversity, energy security, and GHG emissions reduction [Rizzoni 2010]. Hydrogen fuel cell EVs get the energy they need from consuming energy (natural gas or electricity) that could be used in a more direct and energy efficient well-to-wheel pathway propelling vehicles [Bossel 2004]. It also requires colossal investment in infrastructure while the electricity grid is already in place; only minimal infrastructure adjustments are required at the consumer level. Others argue that should EVs dominate the market, current grid capacity is not enough to support concurrent charging. The fact is that the market penetration of EVs will be a lengthy process, which provides sufficient time for grid upgrades underway. The "Smart Grid" is already being deployed and is on its way toward becoming the new standard.

While battery technology breakthroughs continue alongside government policy and regulation updates (GHG emissions reduction goals finalized by numerous countries), crude oil price increases, and fuel / carbon tax introductions, further the premise that battery electric vehicles will eventually be the technology of choice for personal transportation.

8.1. Recommendations

1. Even though the BEV is not currently financially viable, its early introduction can be started to counterbalance the carbon footprint of conventional vehicles, since GHG reduction is also a lengthy process.
2. To assist BEV commercialization, construction of smart charging infrastructure linked to vehicle chargers should also commence early, before the PHEV and BEV become a noticeable added load.
3. Tougher vehicle GHG emission standards could be introduced to encourage auto makers to increase the number of PHEVs in their vehicle fleet, and eventually help the transition to subcompact EVs then to full-size EVs, and shorten this transitional period.

References

A123 Cylindrical cell specification, 2009. http://www.a123systems.com/a123/products (accessed October 11, 2009)

A123 Prismatic cell specification, 2009

AeroVironment, *Why are electric vehicles here to stay*, 2009

Anderman, M., *Technical Review of State of California Air Resources Board White Paper: "Summary of Staff's Preliminary Assessment of the Need for Revisions to the Zero Emission Vehicle Regulation" and Attachments A to C*, January 2010

Anderson, D. *An Evaluation of Current and Future Costs For Lithium-Ion Batteries For Use In Electrified Vehicle Powertrains*, May 2009

Beech Services, "Breakdown of a DC Motor / Gearbox Motor", http://www.beechservices.com/ref_breakdownofdcmotor.asp (accessed April 12, 2010)

Bossel, U. *The Hydrogen Illusion.* Congeneration and On-Site Power Production. March-April, 2004

Brodd, Ralph. *Factors Affecting US Production Decisions: Why are There No Volume Lithium-Ion Battery Manufacturers in the United States?* Prepared for National Institute of Standards, Contract SB 1341-02-W-1445. June 2005.

Buchmann, I. Battery University website, www.batteryuniversity.com, 2009

Burke, A. *Performance Testing of Lithium-ion Batteries of Various Chemistries for EV and PHEV Applications*, 2009 ZEV Symposium, September 2009

CARB Staff Assessment, *Summary of Staff's Preliminary Assessment of the Need for Revisions to the Aero Emission Vehicle Regulation*, November, 2009

Chu, A. *Design Considerations and the Status and Future Plans for Lithium-ion Batteries Using Iron Phosphate in the Cathode*. California Air Resources Board ZEV Symposium. September 27, 2006

Deutsche Bank. *Vehicle Electrification,* Global Markets Research Consumer Autos & Auto Parts, Deutsche Bank, 2010

EPA New test Methods and Calculation Procedures for Fuel Economy Labels, Federal Register Vol. 71, No. 248, December 27, 2006

European Parliament. *Batteries to be collected and recycled, nature protected.* Environment. July 2006. Available at http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+IM-PRESS+20060628BRI09328+FULL-TEXT+DOC+XML+V0//EN#title9

EV1 motor map, Arnett, M. *Modeling and Simulation of a Hybrid Electric Vehicle for the Challenge X Competition*, 2005

EVAmerica Baseline Performance Testing Graphical Spider Chart Comparisons, 2008. http://avt.inel.gov/fsev.shtml (accessed October 20, 2009)

Farrington, R. and J. Rugh. *Impact of Vehicle Air-Conditioning on Fuel Economy, TailpipeEmissions, and Electric Vehicle Range*, National Renewable Energy Laboratory, Golden, Colorado, 2000

Gao, Y., M. Ehsani, *Hybrid Electric Vehicle: Overview and State of the Art,* IEEE ISIE, June, 2005

GM Fuel Cell ETS GMT101X specification, 2009

Green Car Congress, "Nissan and Sumitomo to launch Second-Life Venture for EV Battery Packs; 4R Business Model" Green Car Congress. October 26, 2009. http://www.greencarcongress.com/2009/10/4r-20091020.html (accessed March 16, 2010)

Greene, David L., *Technical Review of State of California Air Resources Board White Paper: "Summary of Staff's Preliminary Assessment of the Need for Revisions to the Zero Emission Vehicle Regulation" and Attachments A to C*, January 2010

HiPower Energy Group, *HiPower Lithium Iron Phosphate cell specification*, 2009

Howell, D. *Progress Report for Energy Storage Research and Development 2008 Annual Progress Report*, January 2009

Kalhammer, F.R., B.M. Kopf, D. Swan, V.P. Roan, and M.P. Walsh. *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007*, Prepared for State of California Air Resources Board, Sacramento, California, April 13, 2007

Kamath, H, *Lithium Ion Batteries for Electric Transportation: Costs and Markets*, Electric Power Research Institute, 2009

Karden, E., S. Ploumen, E. Spijker, D. Kok, D. Kees, P. Phlips, Rekuperatives Bremsen in Fahrzeugen mit 14V-bordnetz, *Energiemanagement und Bordnetze*, Haus der Technik, Essen/Germany, 12/13 October, 2004

Karden, E., S. Ploumen, B. Fricke, T. Miller, K. Snyder, *Energy Storage Devices for future hybrid electric vehicles,* Journal of Power Sources, 2006

Khanna, P. *Canada's approach to reducing GHG emissions from motor vehicles,* Natural Resources Canada, 2009

Kokam, Lithium Polymer cell specification, 2008

Kromer, M. and J. Heywood. *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, LFEE 2007-03 RP. Sloan Automotive Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 2007

Larminie, J. and J. Lowry. *Electric Vehicle Explained,* Wiley, 2003

LG Chem, *LG Chem Lithium Polymer cell specification*, 2004

McCarthy, R. *Assessing Vehicle Electricity Demand Impacts on California Electricity Supply,* Dissertation, University of California, Davis, 2009

MES DEA motor specification, Metric Mind, www.metricmind.com, 2009

NEC Handbook, The National Electrical Code, 1999

NRCAN Office of Energy Efficiency, *Electricity Generation GHG Emissions by Energy Source,* available at http://oee.nrcan-rncan.gc.ca/corporate/statistics/neud/dpa/tableshandbook2/egen_00_2_e_4.cfm?attr=0

NRCAN (Natural Resources Canada). *Premium-Efficiency Motors.* Technical fact sheet M144-20, 2003

Pacific Gas and Electric Company, *Electric Vehicle Infrastructure Installation Guide*, May 1999

Panasonic, *Li-ion cylindrical cell specification*, Green Car Congress, December 2009

Pesaran, A, T. Markel, H. Tataria, and D. Howell, *Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale,* the 23rd International Electric Vehicle Symposium, December 2007

Pesaran, A, K. Smith, and T. Markel, *Impact of the 3Cs of Batteries on PHEV Value Proposition: Cost, Calendar Life, and Cycle Life,* the 9th Advanced Automotive Battery Conference, June 2009

Putois, F. *Market for nickel-cadmium batteries*, Journal of Power Sources, 1995

Rizzoni, G., *Technical Review of State of California Air Resources Board White Paper: "Summary of Staff's Preliminary Assessment of the Need for Revisions to the Zero Emission Vehicle Regulation" and Attachments A to C,* January 2010

Rousseau, A. and M. Pasquier. *Validation of a Hybrid Modeling Software (PSAT) Using its Extension for Prototyping (PSAT-PRO),* Global Powertrain congress, 2001

Ruetschi, P. *Aging mechanisms and service life of lead-acid batteries*, Journal of Power Sources, 2004

SAE J1772, SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler, SAE International, 2010

SAFT NHE Module High Energy Nickel-metal hydride module specification, 2005

Siemens Power Inverter Installation Manual, Rev. 3.00w, February 2004

Sion Power, *Lithium Sulfur cell specification*, 2009. http://www.sionpower.com/product.html (accessed October 11, 2009)

Smart, M.C. *High Power, Gel Polymer Lithium-ion Cells With Improved Low Temperature Performance for NASA and DoD Applications*, Jet Propulsion Laboratory, California Institute of Technology, 2004

Srinivasan, Venkat and Newman, John. *Design and Optimization of a Natural Graphite/Iron Phosphate Lithium-Ion Cell*. Journal of the Electrochemical Society 151, No 10(2004). Pp A1530-A1538.

Tahil, W. *The Trouble with Lithium,* Meridian International Research, December 2006

Thunder Sky Lithium Cobalt Oxide cell specification, 2009. http://www.thunder-sky.com/products_en.asp (accessed on October 11, 2009)

Thunder Sky Lithium Manganese Oxide cell specification, 2009. http://www.thunder-sky.com/products_en.asp (accessed on October 11, 2009)

TM4 Permanent Magnet Electric Motor specification, 2009. http://www.tm4.com/electric_powertrain.aspx (accessed on October 30, 2009)

UQM PowerPhase 100 specification, 2009. http://www.uqm.com/propulsion_specs.php (accessed on October 20, 2009)

US Federal Register, Volume 71, No. 248, December 2006

USABC Goals for Advanced EV Batteries, 2009
http://www.uscar.org/commands/files_download.php?files_id=27 (accessed on November 2, 2009)

Wang, T, P. Zheng, Q. Zhang, and S. Cheng, *Design Characteristics of the Induction Motor Used for Hybrid Electric Vehicle*. IEEE TRANSACTIONS ON MAGNETICS, VOL. 41, NO. 1, January 2005

Ward, J and S. Davis, *2008 Vehicle Technologies Market Report,* US Department of Energy, July 2009

Appendix A. EVAmerica Tested EVs

EVAMERICA | USDOE

GENERAL MOTORS EV1

VEHICLE SPECIFICATIONS

PURPOSE-BUILT VEHICLE
Base Vehicle: 1997 EV1
VIN: 4g5px2250t0100009
Seatbelt Positions: Two
Standard Features:
- Heat Pump Climate Control System
- Cruise Control
- Power Door Locks
- Dual Air Bags
- Power Windows
- Front Disc Brakes
- Power Steering
- Anti-Lock Brakes
- Front Wheel Drive
- Regenerative Braking
- Daytime Running Lights
- AM/FM Stereo w/Cassette and CD Player w/4 Speaker System
- ElectiClear Windshield
- Check Tire Pressure System
- High Voltage Isolation Assurance
- Welded & Bonded Aluminum Alloy Body
- Electronic Key Pad Entry/Vehicle Activation System
- 110V 1.2 kW Convenience Charger

BATTERY
Manufacturer: Delphi
Type: Valve Regulated Lead Acid
Number of Modules: 26
Weight of Module: 18.8 kg
Weight of Pack(s): 1175 kg
Pack Locations: T-Pack Integral
Nominal Module Voltage: 12 V
Nominal System Voltage: 312 V
Nominal Capacity (1C): 53 Ah

WEIGHTS
Design Curb Weight: 2970 lbs
Delivered Curb Weight: 2922 lbs
Distribution F/R: 53/47 %
GVWR: 3410 lbs
GAWR F/R: 1705/1705 lbs
Payload: 440 lbs
Performance Goal: 400 lbs

DIMENSIONS
Wheelbase: 98.9 inches
Track F/R: 57.9/49.0 inches
Length: 169.7 inches
Width: 69.5 inches
Height: 50.5 inches
Ground Clearance: 4.2 inches at GVWR
Performance Goal: 5.0 inches at GVWR

CHARGER
Location: Off-Board
Type: Delco Electronics Inductive 6.6 kW
Input Voltages: 156 to 260 VAC

TIRES
Tire Mfg: Michelin
Tire Model: Proxima RR Radial
Tire Size: P175/65R14
Tire Pressure F/R: 50/50 psi
Spare Installed: No; Self Sealing Tires

TEST NOTES:
1. At various during these range test the Battery Life, Reduced Performance, Service Soon, and Service Now telltales illuminated.
2. Charging time was extended due to high temperature conditions.
3. Specific Energy values were calculated using the number of modules times the module weight.
4. The battery pack data collection voltage signal was reduced 100:1 through a voltage divider installed by General Motors. This was for personnel protection.
5. The Standing Water Test was conducted with a water depth of six inches versus eight inches.

This Vehicle meets all EV America Minimum Requirements listed on back.
Values in **red** indicate the Performance Goal was not met.
All Power and Energy values are DC unless otherwise specified.

PERFORMANCE STATISTICS

ACCELERATION 0-50 mph
At 100% SOC: 6.3 sec
At 50% SOC: 6.7 sec
Max. Power: 116.4 kW
Performance Goal: 13.5 sec at 50% SOC

MAXIMUM SPEED @ 50% SOC
At 1/4 Mile: 78.9 mph
At 1 Mile: 80.4 mph
Performance Goal: 70 mph in one mile

CONSTANT SPEED RANGE @ 45 mph
Range: 135.2 miles
Energy Used: 15.58 kWh
Average Power: 5.19 kW
Efficiency: 115 Wh/mile
Specific Energy: 31.9 Wh/kg

CONSTANT SPEED RANGE @ 60 mph
Range: 89.1 miles
Energy Used: 14.58 kWh
Average Power: 9.79 kW
Efficiency: 164 Wh/mile
Specific Energy: 29.8 Wh/kg

DRIVING CYCLE RANGE
Range per SAE J1634: 78.2 miles
Energy Used: 12.84 kWh
Average Power: 4.06 kW
Efficiency: 164 Wh/mile
Specific Energy: 26.3 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 171.0 feet
Controlled Wet: 214.8 feet
Panic Wet: 211.9 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 55.8 sec
Avg Time @ 50% SOC: 55.4 sec
Avg Time @ 20% SOC: 55.4 sec
Avg ICE Full Size Time: 54.62 sec

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 79.0 mph
Maximum Speed @ 6%: 78.2 mph
Maximum Grade: 53.2%
Time on 3% Grade: 28 min 57 sec
Performance Goal: 15 Min

CHARGING EFFICIENCY
Efficiency: 248 Wh-AC/mile
Energy Cost @ 10 ¢/kWh: 2.48 ¢/mile

CHARGER
Max Charger Ground Current: &lt0.01 mA
Max Battery Leakage Current: &lt0.01 mA mA
Max DC Charge Current: 16.83 Amps
Max AC Charge Current: 28.96 Amps
Pwr Factor @ Max Current: 1.00
THD(V)/(I) @ Max Current: 2.78/4.80 %
Peak Demand: 5.93 kW
Time to Recharge: 5 Hrs 18 min
Performance Goal: 8 hours

This vehicle meets the following EV America Minimum Requirements:

1. The vehicle has a payload of at least 400 pounds.
2. The vehicle does not have a GVWR greater than the OEM GVWR.
3. The OEM GAWRs have not been increased.
4. Seating capacity is a minimum of 2 passengers.
5. A battery recycling plan has been provided.
6. The OEM passenger space has not been intruded upon by the electrical conversion materials.
7. The vehicle has a parking mechanism or parking brake as required by 49 CFR 571.105.
8. The vehicle has a minimum range between charges of at least 50 miles when loaded with two 166-pound occupants and operated at a constant 45 mph.
9. The vehicle manufacturer has certified that this vehicle complies with the Federal Motor Vehicle Safety Standards (FMVSS) applicable on the date of manufacture.
10. The vehicle manufacturer's proposal states that batteries and/or battery enclosures do not intrude into the passenger compartment during or following a frontal barrier, rear barrier and side impact collision and roll-over.
11. Batteries are an advanced design, specifically Nickel-Metal-Hydride (NiMH).
12. The vehicle manufacturer has certified concentrations of explosive gases in the battery box do not exceed 25% of the Lower Explosive Limit (LEL) during and following normal or abnormal charging and operation of the vehicle.
13. The battery charger is capable of recharging the main propulsion battery in less than 12 hours when recharging at 208V single phase 40A maximum.
14. The vehicle manufacturer has certified the charger is capable of accepting input voltages of 208VAC and 240VAC single phase 60 Hertz, with a tolerance of -13% +6% of rated voltage. On-board personnel protection systems are compatible with utility service GFCI protected circuits.
15. The charger has a true power factor of .95 or greater and a harmonic distortion of less than 5% (voltage and current at rated load).
16. The charger is fully automatic, determining when "end of charge" conditions are met and transitioning into a mode that maintains the main propulsion battery at a full state of charge while not overcharging when continuously left on charge.
17. Vehicles do not contain exposed conductors, terminals, contact blocks or devices of any type that create the potential for personnel to be exposed to 50 volts or greater.
18. Vehicles are accompanied with manuals for parts, service, operation and maintenance, interconnection wiring diagrams and schematics.
19. The vehicle has a state of charge indicator for the main propulsion batteries.
20. The vehicle has a state of charge indicator for the main propulsion batteries.
21. The vehicle has a power or current indicator.
22. Under static conditions, leakage current from propulsion system to vehicle chassis is less than 1 mA.
23. Ground currents from a grounded chassis during charging does not exceed 5 mA.
24. Replacement tires are commercially available to the end user.
25. The vehicle has the following interlocks:
    a). The controller does not energize in any drive selector position other than Park" or "Neutral"
    b). The start key is removable only in the "Off' position, with the drive selector in "Park"
    c). The controller does not initially energize or excite with a preexisting accelerator input.
26. The vehicle manufacturer has certified this vehicle complies with FCC requirements for unintentional emitted electromagnetic radiation, as identified in 47 CFR 15, Subpart B, "Unintentional Radiators."
27. The vehicle manufacturer has certified failure of a battery or battery pack is deemed to have occurred if the actual battery capacity is not at least 80% of the nominal ampere hour capacity.
28. The vehicle is equipped with an automatic disconnect and a manual service disconnect for the main propulsion batteries which are clearly labeled.
29. The charging system is compatible with circuit breaker type GFCI systems.
30. Material Safety Data Sheets (MSDS) for all on-board batteries have been supplied.
31. The level of charge below which the batteries should not be discharged and how the controller automatically limits battery discharge below this level have been identified by the manufacturer.

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EVAMERICA	USDOE

1997 Chevrolet S-10 Electric

VEHICLE SPECIFICATIONS

PURPOSE-BUILT VEHICLE
Base Vehicle: 1997 Chevrolet S-10
VIN: 1GCDE14H4V80003EX
Seatbelt Positions: Three
Standard Features:
- Heat Pump Climate Control System
- Auxillary Diesel Fuel Fired Heater (Only operates Below 40 F)
- Cruise Control
- Tilt Steering Wheel
- Front Wheel Drive
- Power Steering
- Power Brakes
- Anti-Lock Brakes
- Front Disk Brakes
- Regenerative Braking
- Drivers Side Air Bags
- AM/FM Stereo Radio
- Half-Bed Tonneau Cover

BATTERY
Manufacturer: Delphi Energy
Type: Valve Regulated Lead Acid
Number of Modules: 26
Weight of Module: 19 kg
Weight of Pack(s): 575 kg
Pack Locations: Underbody
Nominal Module Voltage: 12 V
Nominal System Voltage: 312 V
Nominal Capacity (C/2): 48 Ah

WEIGHTS
Design Curb Weight: 4300 lbs
Delivered Curb Weight: 4199 lbs
Distribution F/R: 48/52 %
GVWR: 5150 lbs
GAWR F/R: 2700/2900 lbs
Payload: 951 lbs
Performance Goal: 600 lbs

DIMENSIONS
Wheelbase: 108.3 inches
Track F/R: 57.2/54.9 inches
Length: 188.9 inches
Width: 67.8 inches
Height: 62.4 inches
Ground Clearance: 5.0 inches at GVWR
Performance Goal: 5.0 inches at GVWR

CHARGER
Location: Off-Board
Type: Delco Electronics Inductive 6.6 kW
Input Voltages: 165 to 260 VAC

TIRES
Tire Mfg: Uniroyal
Tire Model: Tigerpaw AWP Radial
Tire Size: P205/75R15
Tire Pressure F/R: 51/51 psi
Spare Installed: No

PERFORMANCE STATISTICS

ACCELERATION 0-50 mph
At 100% SOC: 9.75 sec
At 50% SOC: 10.35 sec
Max. Power: 104.3 kW
Performance Goal: 13.5 sec at 50% SOC

MAXIMUM SPEED @ 50% SOC[1]
At 1/4 Mile: 67.6 mph
At 1 Mile: 69.3 mph
Performance Goal: 70 mph in one mile

CONSTANT SPEED RANGE @ 45 mph
Range: 60.4 miles
Energy Used: 12.99 kWh
Average Power: 9.70 kW
Efficiency: 215 Wh/mile
Specific Energy: 22.2 Wh/kg

CONSTANT SPEED RANGE @ 60 mph
Range: 38.8 miles
Energy Used: 11.93 kWh
Average Power: 18.30 kW
Efficiency: 307 Wh/mile
Specific Energy: 20.7 Wh/kg

DRIVING CYCLE RANGE
Range per SAE J1634: 43.8 miles
Energy Used: 12.81 kWh
Average Power: 6.98 kW
Efficiency: 292 Wh/mile
Specific Energy: 22.3 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 182.2 feet
Controlled Wet: 216.3 feet
Panic Wet: 192.1 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 56.2 sec
Avg Time @ 50% SOC: 55.8 sec
Avg Time @ 20% SOC: 55.5 sec
Avg S-10 ICE Time: 58.3 sec[2]

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 68.0 mph
Maximum Speed @ 6%: 66.5 mph
Maximum Grade: 36.4%
Time on 3% Grade: 10 min 3 sec[3]
Performance Goal: 15 Min from 50% SOC

CHARGING EFFICIENCY
Efficiency: 470 Wh-AC/mile
Energy Cost @ 10 ¢/kWh: 4.70 ¢/mile

CHARGER
Max Charger Ground Current: <0.01 mA
Max Battery Leakage Current: <0.01 mA
Max DC Charge Current: 16.9 Amps
Max AC Charge Current: 19.4 Amps
Pwr Factor @ Max Current: 0.97
THD(I) @ Max Current: 7.70 %
Peak Demand: 6.59 kW
Time to Recharge: 5 Hrs 15 min
Performance Goal: 8 hours

TEST NOTES:
1. Vehicle maximum speed is software limited. Chevrolet will be issuing a software modification to allow a maximum speed greater than 70 mph subsequent to completion of EV America Testing.
2. ICE Vehicle tested was a 1992 rear wheel drive with a 4.3 liter V-6 engine.
3. Vehicle complete 21 minutes 3 seconds from 100% SOC.
4. Cruise control failed to engage on two occasions. Vehicle required restart before cruise control could be engaged.
5. The battery pack data collection voltage signal was reduced 100:1 through a voltage divider installed by Chevrolet. This was for personnel protection.

This Vehicle meets all EV America Minimum Requirements listed on back.
Values in **red** indicate the Performance Goal was not met.
All Power and Energy values are DC unless otherwise specified.

EV AMERICA | USDOE

PERFORMANCE STATISTICS

1998 Ford Ranger EV

VEHICLE SPECIFICATIONS

PURPOSE-BUILT VEHICLE
Base Vehicle: 1998 Ford Ranger
VIN: 1FTCR100XWSA00951
Seatbelt Positions: Three
Standard Features:
- AM/FM Stereo Radio
- Tilt Steering Wheel
- Cabin Heat
- Dual Air Bags
- Power Steering (Electro-Hydraulic)
- Power Brakes
- Four Wheel Disc Brakes
- Four Wheel Anti-Lock Brakes
- Regenerative Braking
- Full-Bed Tonneau Cover
- Aluminum Wheels
- Low Rolling Resistance Tires

Options As Tested
- Air Conditioning
- Battery Heater

BATTERY
Manufacturer: Delphi
Type: VRLA
Number of Modules: 39
Weight of Module: 19.3 kg
Weight of Pack(s): 870.1 kg
Pack Locations: Underbody
Nominal Module Voltage: 8 V
Nominal System Voltage: 312 V
Nominal Capacity (C/2): 60 Ah

WEIGHTS
Design Curb Weight: 4700 lbs
Delivered Curb Weight: 4731 lbs
Distribution F/R: 51/49%
GVWR: 5400 lbs
GAWR F/R: 2659/2808 lbs
Payload: 700 lbs[1]
Performance Goal: 600 lbs

DIMENSIONS
Wheelbase: 111.6 inches
Track F/R: 58.6/57.3 inches
Length: 187.5 inches
Width: 69.4 inches
Height: 66.0 inches
Ground Clearance: 5.2 inches at GVWR
Performance Goal: 5.0 inches at GVWR

CHARGER
Location: On-board w/Off-Board PCS[2]
Type: Conductive
Input Voltages: 187 to 264 VAC

TIRES
Tire Mfg: Uniroyal
Tire Model: Tigerpaw AWP Radial
Tire Size: P255/70R15
Tire Pressure F/R: 50/50 psi
Spare Installed: No

TEST NOTES:
1. Design payload value; value as tested was 669 lbs.
2. Required Power Control Station (PCS) is purchased separately and cannot be used with a GFCI protected circuit.
3. Testing was terminated upon illumination of the Power Limit telltale.
4. ICE Vehicle tested was a 1992 rear wheel drive with a 4.3 liter V-6 engine.
5. Vehicle completed 21 minutes 54 seconds from 100% SOC.
6. Charging time was extended due to high temperature conditions.
7. The vehicle's Battery Control Module failed during the Test Program and was replaced
8. One battery module failed during the Test Program and was replaced.
9. Vehicle was removed from the Test Program for three 24-hour repair periods.

This Vehicle meets all EV America Minimum Requirements listed on back.
Values in **red** indicate the Performance Goal was not met.
All Power and Energy values are DC unless otherwise specified.

ACCELERATION 0-50 mph
At 100% SOC: 11.6 sec
At 50% SOC: 12.3 sec
Max. Power: 87.4 kW
Performance Goal: 13.5 sec at 50% SOC

MAXIMUM SPEED @ 50% SOC
At 1/4 Mile: 61.6 mph
At 1 Mile: 74.5 mph
Performance Goal: 70 mph in one mile

CONSTANT SPEED RANGE @ 45 mph[3]
Range: 86.9 miles
Energy Used: 20.63 kWh
Average Power: 10.71 kW
Efficiency: 237 Wh/mile
Specific Energy: 23.7 Wh/kg

CONSTANT SPEED RANGE @ 60 mph[3]
Range: 57.9 miles
Energy Used: 20.60 kWh
Average Power: 21.41 kW
Efficiency: 356 Wh/mile
Specific Energy: 23.7 Wh/kg

DRIVING CYCLE RANGE[3]
Range per SAE J1634: 65.1 miles
Energy Used: 21.96 kWh
Average Power: 9.54 kW
Efficiency: 337 Wh/mile
Specific Energy: 25.2 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 162.8 feet
Controlled Wet: 202.1 feet
Panic Wet: 201.1 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 56.9 sec
Avg Time @ 50% SOC: 56.8 sec
Avg Time @ 20% SOC: 56.8 sec
Avg S-10 ICE Time: 58.3 sec[4]

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 68.3 mph
Maximum Speed @ 6%: 58.1 mph
Maximum Grade: 34.4%
Time on 3% Grade: 10 min 48 sec[3,5]
Performance Goal: 15 Min from 50% SOC

CHARGING EFFICIENCY
Efficiency: 484 Wh-AC/mile
Energy Cost @ 10 ¢/kWh: 4.84 ¢/mile

CHARGER
Max Charger Ground Current: <0.01 mA
Max Battery Leakage Current: 0.02 MIU
Max DC Charge Current: 13.69 Amps
Max AC Charge Current: 20.92 Amps
Pwr Factor @ Max Current: 0.989
THD(I) @ Max Current: 3.30%
Peak Demand: 4.16 kW-AC
Time to Recharge: 8 Hrs 51 min[6]
Performance Goal: 8 hours

EVAMERICA	USDOE

PERFORMANCE STATISTICS

1999 GENERAL MOTORS EV1 w/NiMH

VEHICLE SPECIFICATIONS

PURPOSE-BUILT VEHICLE
Base Vehicle: 1999 EV1 NiMH
VIN: 4G5PX2256X00076
Seatbelt Positions: Two
Standard Features:
Cruise Control
Dual Airbags
Power Steering
Traction Control
Daytime Running Lamps
Power Windows, Mirrors & Door Locks
AM/FM Stereo w/Cassette and CD Player
Regenerative Braking with Coastdown
Electro-Hydraulic Braking with ABS
Electro Windshield Defogger & De-Icer
Lightweight Bonded Aluminum Structure
Check Tire Pressure System
High Voltage Isolation Assurance
Heat Pump Climate Control System w/Pre-Conditioning Feature
Electronic Key Pad Entry/Activation

BATTERY
Manufacturer: Ovonic Energy Products
Type: Nickel Metal Hydride
Number of Modules: 26
Weight of Module: 18.3 kg
Weight of Pack(s): 481 kg
Pack Locations: Integral T-Pack
Nominal Module Voltage: 13.2 V
Nominal System Voltage: 343 V
Nominal Capacity (C/2): 85 A/H

WEIGHTS
Design Curb Weight: 2970 lbs
Delivered Curb Weight: 2848 lbs
Distribution F/R: 53/47 %
GVWR: 3410 lbs
GAWR F/R: 1705/1705 lbs
Payload: 440 lbs
Performance Goal: 400 lbs

DIMENSIONS
Wheelbase: 98.9 inches
Track F/R: 57.9/49.0 inches
Length: 169.7 inches
Width: 69.5 inches
Height: 50.5 inches
Ground Clearance: 4.3 inches at GVWR
Performance Goal: 5.0 inches at GVWR

CHARGER
Location: Off-Board
Type: Magne Charge Inductive 6.6 kW
Input Voltages: 191 - 256 VAC

TIRES
Tire Mfg: Michelin
Tire Model: Proxima RR™ Radial
Tire Size: P175/65R14
Tire Pressure F/R: 50/50 psi
Spare Installed: No; Self Sealing Tires

TEST NOTES:
1. At test termination vehicle was still able to maintain required drive schedule.
2. Testing was terminated upon illumination of the Service Now Tell Tale.
3. As detailed in the Owners Manual, the Battery Life, Reduced Performance, Service Soon and Service Now telltales illuminated during the drive schedules.
4. On 3% Grade, this vehicle completed 67 minutes 9 seconds from 100% SOC.
5. Standing water test was conducted in 6" versus 8" identified in procedure.
6. General Motors provided instrumentation connections, including a 100:1 voltage divider and battery pack thermocouple.
7. Vehicle was removed from Test Program for one 24-hour repair period to replace a battery module.

This Vehicle meets all EV America Minimum Requirements listed on back.
Values in **red** indicate the Performance Goal was not met.
All Power and Energy values are DC unless otherwise specified.

ACCELERATION 0-50 mph
At 100% SOC: 6.3 sec
At 50% SOC: 6.5 sec
Max. Power: 104.0 kW
Performance Goal: 13.5 sec

MAXIMUM SPEED @ 50% SOC
At 1/4 Mile: 78.3 mph
At 1 Mile: 79.6 mph
Performance Goal: 70 mph in One Mile

CONSTANT SPEED RANGE @ 45 mph[1,2,3]
Range: 220.7 miles
Energy Used: 28.15 kWh
Average Power: 5.81 kW
Efficiency: 127 Wh/mile
Specific Energy: 58.5 Wh/kg

CONSTANT SPEED RANGE @ 60 mph[1,2,3]
Range: 160.6 miles
Energy Used: 27.04 kWh
Average Power: 10.28 kW
Efficiency: 168 Wh/mile
Specific Energy: 56.2 Wh/kg

DRIVING CYCLE RANGE[1,2,3]
Range per SAE J1634: 140.3 miles
Energy Used: 25.14 kWh
Average Power: 5.28 kW
Efficiency: 179 Wh/mile
Specific Energy: 52.3 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 160.0 feet
Controlled Wet: 158.4 feet
Panic Wet: 172.4 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 55.1 sec
Avg Time @ 50% SOC: 54.4 sec
Avg Time @ 20% SOC: 54.3 sec
Avg Dodge Neon Time: 54.6 sec

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 78.8 mph
Maximum Speed @ 6%: 78.3 mph
Maximum Grade: 56.9%
Time on 3% Grade: 32 min 25 sec[4]
Performance Goal: 15 min from 50% SOC

CHARGING EFFICIENCY
Efficiency: 373 Wh-AC/mile
Energy Cost: 3.73 ¢/mile

CHARGER
Max Charger Ground Current: <0.01 mA
Max Battery Leakage Current: <0.01 MIU
Max DC Charge Current: 13.75 Amps
Max AC Charge Current: 31.86 Amps
Pwr Factor @ Max Current: 0.998
THD(I) @ Max Current: 5.32%
Peak Demand: 6.7 kW
Time to Recharge: 6 Hrs 58 min
Performance Goal: 8 hours

EV AMERICA

USDOE

PERFORMANCE STATISTICS

1998 Chevrolet S-10 Electric w/NiMH

VEHICLE SPECIFICATIONS

PURPOSE-BUILT VEHICLE
Base Vehicle: 1998 S-10
VIN: 1GCDE14H1W8122580
Seatbelt Positions: Three
Standard Features:
- Heat Pump Climate Control System
- Auxillary Diesel Fuel Fired Heater (Only operates Below 37°F)
- Cruise Control
- Power Steering
- Tilt Steering Wheel
- 4-wheel Anti-Lock Power Assisted Brakes
- Regenerative Braking
- Propulsion Battery Thermal Management System
- Driver and Passenger-Side Air Bags (w/Passenger-Side Deactivation Switch)
- AM/FM Stereo Radio
- Half-Bed Tonneau Cover

BATTERY
Manufacturer: Ovonic Energy Products
Type: Nickel Metal Hydride
Number of Modules: 26
Weight of Module: 18.3 kg
Weight of Pack(s): 490.5 kg
Pack Locations: Underbody
Nominal Module Voltage: 13.2 V
Nominal System Voltage: 343 V
Nominal Capacity (C/2): 85 Ah

WEIGHTS
Design Curb Weight: 4200 lbs
Delivered Curb Weight: 4230 lbs
Distribution F/R: 50/50 %
GVWR: 5150 lbs
GAWR F/R: 2700/2900 lbs
Payload: 950 lbs[5]
Performance Goal: 600 lbs

DIMENSIONS
Wheelbase: 108.2 inches
Track F/R: 56.9/55.0 inches
Length: 190.8 inches
Width: 68.3 inches
Height: 62.4 inches
Ground Clearance: 5.2 inches at GVWR
Performance Goal: 5.0 inches at GVWR

CHARGER
Location: Off-Board
Type: Magne Charge Inductive 6.6 kW
Input Voltages: 191 - 256 VAC

TIRES
Tire Mfg: Uniroyal
Tire Model: Tigerpaw AWP Radial
Tire Size: P205/75R15
Tire Pressure F/R: 50/50 psi
Spare Installed: No

TEST NOTES:
1. At test termination vehicle was still able to maintain required drive schedule.
2. Testing was terminated upon illumination of the Service Now TellTale.
3. As detailed in the Owners Manual, the Battery Life and Service Soon telltales illuminated during the drive schedules.
4. On 3% Grade, this vehicle completed 48 minutes 7 seconds from 100% SOC.
5. As-delivered Payload was 920 lbs.
6. General Motors provided instrumentation connections, including a 100:1 voltage divider and battery pack thermocouple.
7. Vehicle was removed from Test Program for one 24-hour period to replace a fan control switch.

This Vehicle meets all EV America Minimum Requirements listed on back.
Values in **red** indicate the Performance Goal was not met.
All Power and Energy values are DC unless otherwise specified.

ACCELERATION 0-50 mph
At 100% SOC: 9.9 sec
At 50% SOC: 10.9 sec
Max. Power: 98.5 kW
Performance Goal: 13.5 sec

MAXIMUM SPEED @ 50% SOC
At 1/4 Mile: 65.9 mph
At 1 Mile: 71.0 mph
Performance Goal: 70 mph in One Mile

CONSTANT SPEED RANGE @ 45 mph[1,2,3]
Range: 130.6 miles
Energy Used: 27.92 kWh
Average Power: 9.69 kW
Efficiency: 214 Wh/mile
Specific Energy: 56.9 Wh/kg

CONSTANT SPEED RANGE @ 60 mph[1,2,3]
Range: 87.7 miles
Energy Used: 27.17 kWh
Average Power: 18.96 kW
Efficiency: 310 Wh/mile
Specific Energy: 55.4 Wh/kg

DRIVING CYCLE RANGE[1,2,3]
Range per SAE J1634: 95.3 miles
Energy Used: 26.35 kWh
Average Power: 7.69 kW
Efficiency: 276 Wh/mile
Specific Energy: 53.7 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 177.9 feet
Controlled Wet: 196.6 feet
Panic Wet: 194.1 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 56.0 sec
Avg Time @ 50% SOC: 56.0 sec
Avg Time @ 20% SOC: 56.0 sec
Avg S-10 ICE Time: 58.3 sec

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 69.3 mph
Maximum Speed @ 6%: 66.3 mph
Maximum Grade: 31.4%
Time on 3% Grade: 23 min 50 sec[4]
Performance Goal: 15 Min from 50% SOC

CHARGING EFFICIENCY
Efficiency: 794 Wh-AC/mile
Energy Cost @ 10 ¢/kWh: 7.94 ¢/mile

CHARGER
Max Charger Ground Current: <0.01 mA
Max Battery Leakage Current: <0.01 MIU
Max DC Charge Current: 13.13 Amps
Max AC Charge Current: 31.55 Amps
Pwr Factor @ Max Current: 0.999
THD(I) @ Max Current: 5.0 %
Peak Demand: 6.46 kW
Time to Recharge: 8 Hrs 54 min
Performance Goal: 8 hours

EV AMERICA | USDOE

PERFORMANCE STATISTICS

1999 Ford Ranger

VEHICLE SPECIFICATIONS

PURPOSE-BUILT VEHICLE
Base Vehicle: 1999 Ford Ranger
VIN: 1FTZR0872XTA00007
Seatbelt Positions: Three
Standard Features:
- AM/FM Stereo Radio
- Tilt Steering Wheel
- Cabin Heat
- Dual Air Bags
- Power Steering (electro-hydraulic)
- Power Brakes
- Four Wheel Disc Brakes
- Four Wheel Anti-Lock Brakes
- Regenerative Braking
- Full-Bed Tonneau Cover
- Aluminum Wheels
- Low Rolling Resistance Tires

Options As Tested
- Air Conditioning

BATTERY
Manufacturer: Motorcraft(Panasonic)
Type: Nickel Metal Hydride
Number of Modules: 25
Weight of Module: 18.54 kg
Weight of Pack(s): 485 kg
Pack Locations: Underbody
Nominal Module Voltage: 12 V
Nominal System Voltage: 300 V
Nominal Capacity (C/3): 95 Ah

WEIGHTS
Design Curb Weight: 4196 lbs
Delivered Curb Weight: 4144 lbs
Distribution F/R: 51/49%
GVWR: 5350 lbs
GAWR F/R: 2710/2900 lbs
Payload: 1154 lbs[1]
Performance Goal: 600 lbs

DIMENSIONS
Wheelbase: 112.4 inches
Track F/R: 58.7/57.3 inches
Length: 187.4 inches
Width: 69.8 inches
Height: 66.0 inches
Ground Clearance: 5.0 inches at GVWR
Performance Goal: 5.0 inches at GVWR

CHARGER
Location: Underhood
Type: Conductive
Input Voltages: 187 to 260 VAC

TIRES
Tire Mfg: Uniroyal
Tire Model: Tigerpaw AWP Radial
Tire Size: P255/70R15
Tire Pressure F/R: 51/51 psi[2]
Spare Installed: No

ACCELERATION 0-50 mph
At 100% SOC: 10.3 sec
At 50% SOC: 11.2 sec
Max. Power: 84.13 kW
Performance Goal: 13.5 sec at 50% SOC

MAXIMUM SPEED @ 50% SOC
At 1/4 Mile: 62.1 mph
At 1 Mile: 74.6 mph
Performance Goal: 70 mph in one mile

CONSTANT SPEED RANGE @ 45 mph[3,4,5]
Range: 115.0 miles
Energy Used: 27.81 kWh
Average Power: 10.94 kW
Efficiency: 242 Wh/mile
Specific Energy: 57.3 Wh/kg

CONSTANT SPEED RANGE @ 60 mph[3,4,5]
Range: 74.2 miles
Energy Used: 26.83 kWh
Average Power: 21.52 kW
Efficiency: 362 Wh/mile
Specific Energy: 55.3 Wh/kg

DRIVING CYCLE RANGE[3,4,5]
Range per SAE J1634: 82.4 miles
Energy Used: 25.95 kWh
Average Power: 8.32 kW
Efficiency: 315 Wh/mile
Specific Energy: 53.5 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 166.6 feet
Controlled Wet: 215.2 feet
Panic Wet: 195.7 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 56.5 sec
Avg Time @ 50% SOC: 55.8 sec
Avg Time @ 20% SOC: 55.4 sec
Avg S-10 ICE Time: 58.3 sec

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 67.4 mph
Maximum Speed @ 6%: 58.9 mph
Maximum Grade: 39.9%
Time on 3% Grade: 19 min 34 sec[5,6,7]
Performance Goal: 15 Min

CHARGING EFFICIENCY
Efficiency: 485 Wh-AC/mile
Energy Cost @ 10 ¢/kWh: 4.85 ¢/mile

CHARGER
Max Charger Ground Current: <0.01 mA
Max Battery Leakage Current: <0.01 MIU
Max DC Charge Current: 13.57 Amps
Max AC Charge Current: 24.96 Amps
Pwr Factor @ Max Current: 0.996
THD(I) @ Max Current: 5.01%
Peak Demand: 4.98 kW-AC
Time to Recharge: 8 Hrs 13 min
Performance Goal: 8 hours

TEST NOTES:
1. Design Payload Value. Value as tested was 1206 lbs.
2. DOT Side-wall Tire Air Pressure Rating; Ford recommends 50/50 psi.
3. Test was terminated upon receipt of the flashing Power Limit telltale.
4. At test termination, vehicle was still able to maintain the required drive schedule.
5. As detailed in the Owner's Manual, several telltales illuminated during the drive schedule.
6. At test termination, vehicle was not able to maintain the required drive schedule.
7. On 3% grade, this vehicle completed 38 minutes 55 seconds from 100% SOC.

This Vehicle meets all EV America Minimum Requirements listed on back.
Values in **red** indicate the Performance Goal was not met.
All Power and Energy values are DC unless otherwise specified.

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1999 EPIC w/ NiMH Batteries

VEHICLE SPECIFICATIONS

Base Vehicle: Dodge Caravan
VIN: 2B4G1587XR179939
Standard Features:
- AM/FM Stereo Radio w/ Cassette Tape
- Tilt Steering Wheel
- Air Conditioning
- Heater
- Front Wheel Drive
- Driver & Front Passenger Air Bags
- Power Steering
- Power Brakes
- Front Wheel Disc Brakes
- Anti-Lock Brakes
- Regenerative Braking
- Power Door Locks
- Low Rolling Resistance Tires

BATTERY
Manufacturer: SAFT
Type: Nickel Metal Hydride
Number of Modules: 14
Module Weight: 38 kg (w/coolant)
Pack Weight: 532 kg (w/coolant)
Pack(s) Location: Underbody
Nominal Module Voltage: 24 V
Nominal System Voltage: 336 V
Nominal Capacity (C/3): 82 A/H

WEIGHTS
Design Curb Weight: 4,835 lbs
Delivered Curb Weight: 4,878 lbs
Distribution F/R: 52/48 %
GVWR: 5,800 lbs
GAWR F/R: 2,850/3,100 lbs
Payload: 945 lbs [1]
Performance Goal: 600 lbs

DIMENSIONS
Wheelbase: 113.9 inches
Track F/R: 62.9/64.2 inches
Length: 185.8 inches
Width: 75.8 inches
Height: 70.3 inches
Ground Clearance: 5.2 inches @ GVWR
Performance Goal: 5.0 inches @ GVWR

CHARGER
Location: Off-board
Type: Lockheed-Martin Conductive
Input Voltages: See Test Note 2

TIRES
Tire Mfg: Goodyear
Tire Model: Momentum
Tire Size: P205/75R15 XL
Tire Pressure F/R: 50/50 psi
Spare Installed: Yes (space-saver)

TEST NOTES:
1. Design Payload Value. Value as tested was 922 lbs.
2. Charger can be powered from 208V or 240V single phase or 208V three phase AC.
3. Test was terminated upon illumination of the Power Limit telltale.
4. At test termination, vehicle was still able to maintain the required drive schedule speed.
5. Charge was accomplished using 40A 208V single-phase power.
6. Time to recharge on 60A 208V three-phase power was 4 hours 12 minutes.
7. Time to recharge on 60A 240V single-phase was 6 hours 0 minutes.
8. Vehicle was removed from the Test Program for two 24-hour repair periods to replace a failed O-ring in the air conditioning system (NCR 99-001-79939) and one 24-hour repair period to replace the battery pack (NCR 99-002-79939).

This vehicle meets all EV America Minimum Requirements listed on back.

Values in **red** indicate the Performance Goal was not met. • All Power and Energy values are DC unless otherwise specified.

PERFORMANCE STATISTICS

ACCELERATION 0-50 mph
At 100% SOC: 12.3 sec
At 50% SOC: 12.9 sec
Max Power: 91.3 kW
Performance Goal: 13.5 sec

MAXIMUM SPEED @ 50% SOC
At 1/4 Mile: 61.7 mph
In 1 Mile: 78.0 mph
Performance Goal: 70 mph in One Mile

CONSTANT SPEED RANGE @ 45 mph [3,4]
Range: 116.1 miles
Energy Used: 28.48 kW
Average Power: 11.09 kW
Efficiency: 245 Wh/mile
Specific Energy: 55.1 Wh/kg

CONSTANT SPEED RANGE @ 60 mph [3]
Range: 81.2 miles
Energy Used: 27.61 kWh
Average Power: 20.18 kW
Efficiency: 340 Wh/mile
Specific Energy: 51.9 Wh/kg

DRIVING CYCLE RANGE [3]
Range per SAE J1634: 79.1 miles
Energy Used: 29.42 kWh
Average Power: 9.91 kW
Efficiency: 372 Wh/mile
Specific Energy: 55.3 Wh/kg
Performance Goal: 60 miles

BRAKING FROM 60 mph
Controlled Dry: 179.0 feet
Controlled Wet: 238.0 feet
Panic Wet: 197.0 feet
Course Deviation: 0.0 feet

HANDLING
Avg Time @ 90% SOC: 58.4 sec
Avg Time @ 50% SOC: 57.1 sec
Avg Time @ 20% SOC: 57.7 sec
Avg S-10 (ICE) Time: 58.3 sec

GRADEABILITY (Calculated)
Maximum Speed @ 3%: 67.2 mph
Maximum Speed @ 6%: 56.8 mph
Maximum Grade: 31.6%
Time on 3% Grade: 18 min 55 sec
Performance Goal: 15 min

CHARGING EFFICIENCY
Efficiency: 784 Wh-AC/mile
Energy Cost: @ 10¢/kWh: 7.84¢/mile

CHARGER
Max Charger Ground Current: 0.243 mA
Max Battery Leakage Current: 0.463 MIU
Max DC Charge Current: 17.30 Amps
Max AC Charge Current: 35.40 Amps
Pwr Factor @ Max Current: 0.998
THD(I) @ Max Current: 8.63%
Peak Demand: 7.05 kW
Time to Recharge: 8 hrs 45 min [5,6,7]
Performance Goal: 8 hours

Appendix B. Vehicle Specification

Table B-1, Vehicle Parameters

Vehicle	Mass, kg	Frontal Area, m^2	Drag coefficient	Tire Rolling Resistance	Motor	Battery Capacity, kWh		
						PbA	**NiMH**	**Li**
GM EV1	1325	2.03	0.19	0.0056	Induction	18.7	29.2	
Chevy S10 Electric	1904	2.62	0.40	0.009	Induction	18.7	29.2	
Ford Ranger Electric	2145	2.84	0.44	0.009	Induction	28.1	28.5	
Chrysler Epic	2212	2.90	0.4	0.010	Induction	N/A	27.6	
Electric Saturn Vue	2130	2.64	0.386	0.0068	Induction	N/A	N/A	79.9

Appendix C. Drive Cycles

Table C-1, EPA Drive Cycles

Drive Cycle	**Average Speed,** km/h	**Top Speed,** km/h	**Distance,** km	**Accessory load,** kW
UDDS	31.5	91.2	12.0	0.5
HWFET	77.7	96.4	16.5	0.5
US06	77.2	129.2	12.9	0.5
SC03	34.9	88.2	5.8	3.5
Combined	48.0	96.4	28.5	0.5
Towing on 3.5% grade	71.4	72	24.4	0.5

*Drive cycle second by second data can be found at www.epa.gov/nvfel/testing/dynamometer.htm

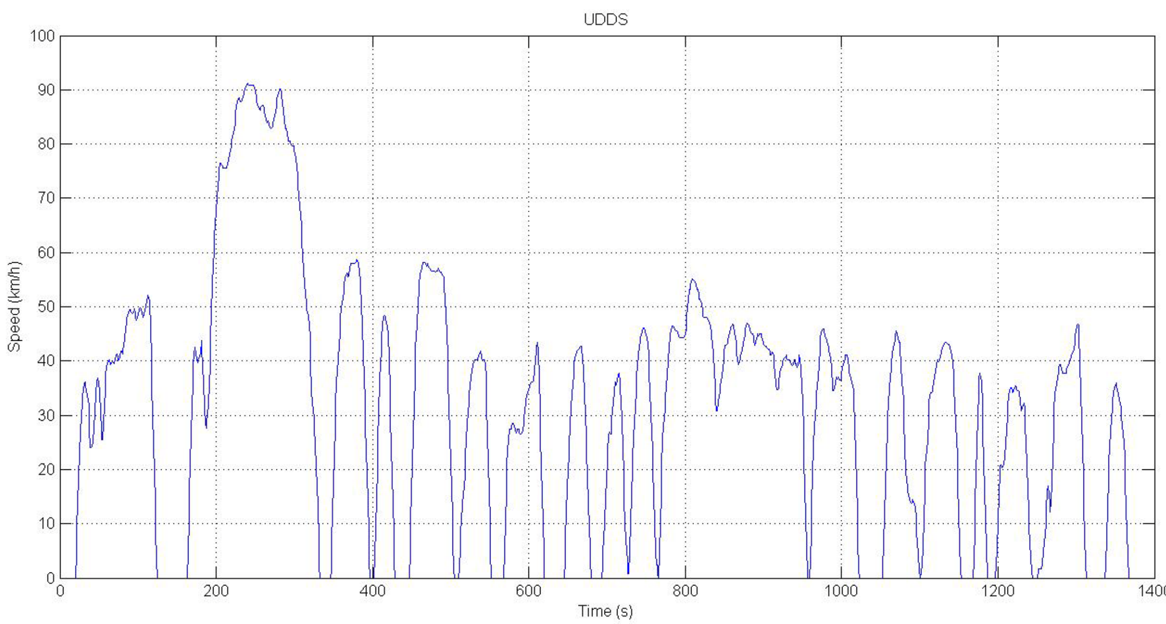


Figure C-1, EPA UDDS

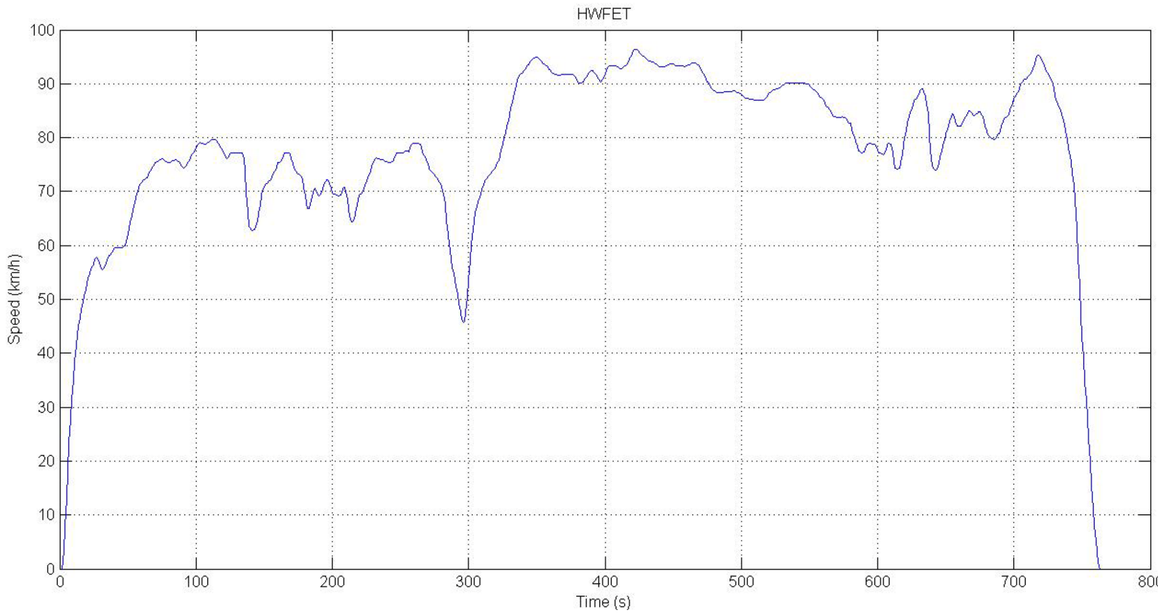


Figure C-2, EPA HWFET

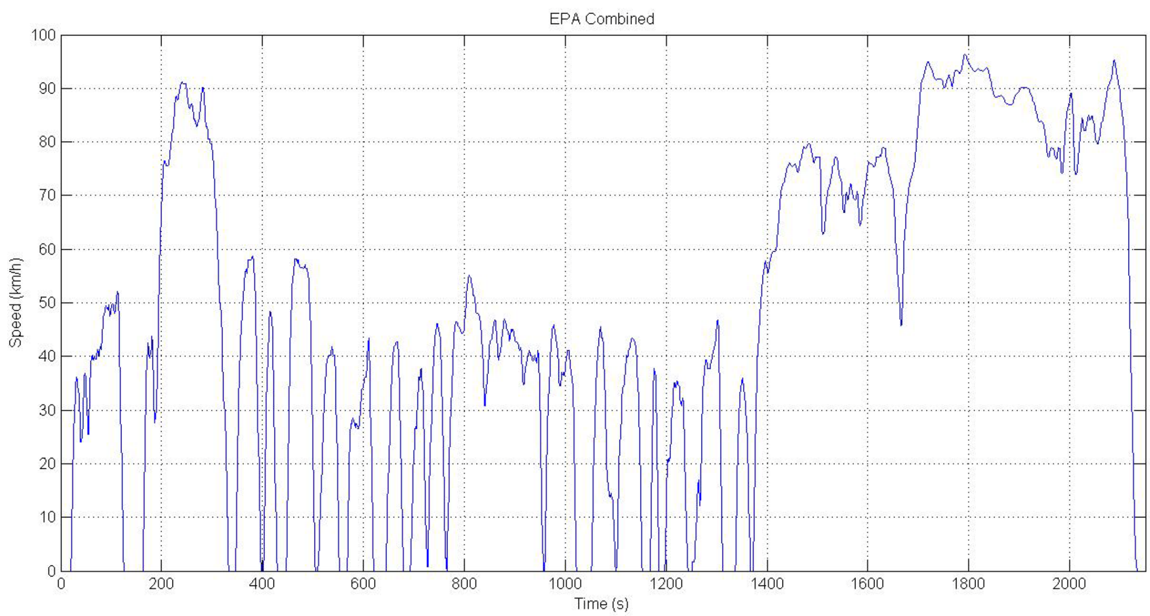


Figure C-3, EPA Combined

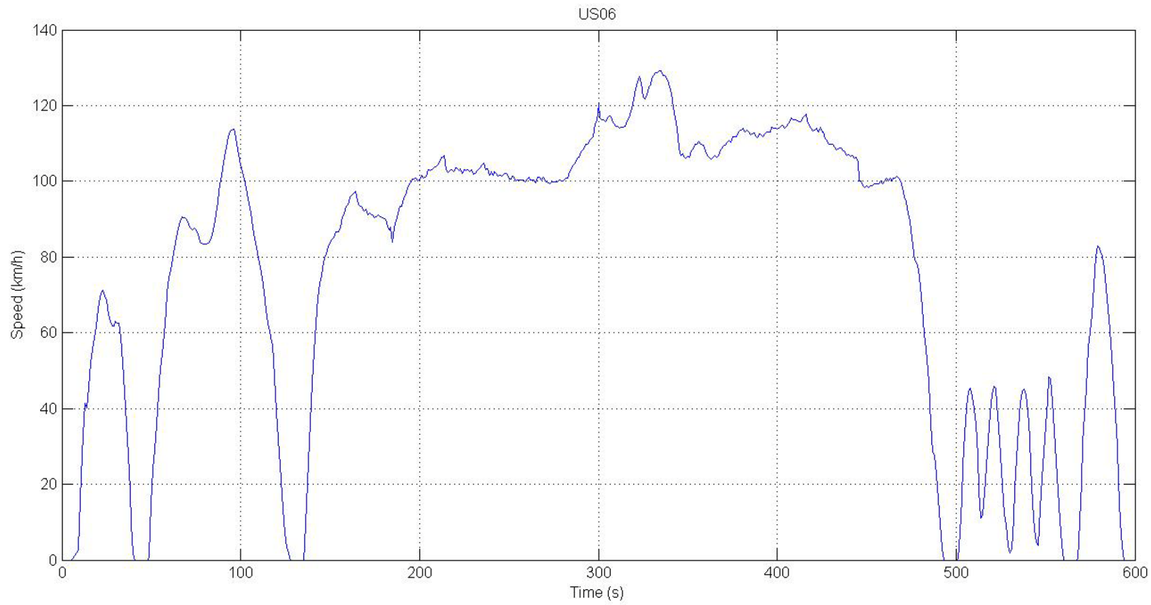


Figure C-4, EPA US06

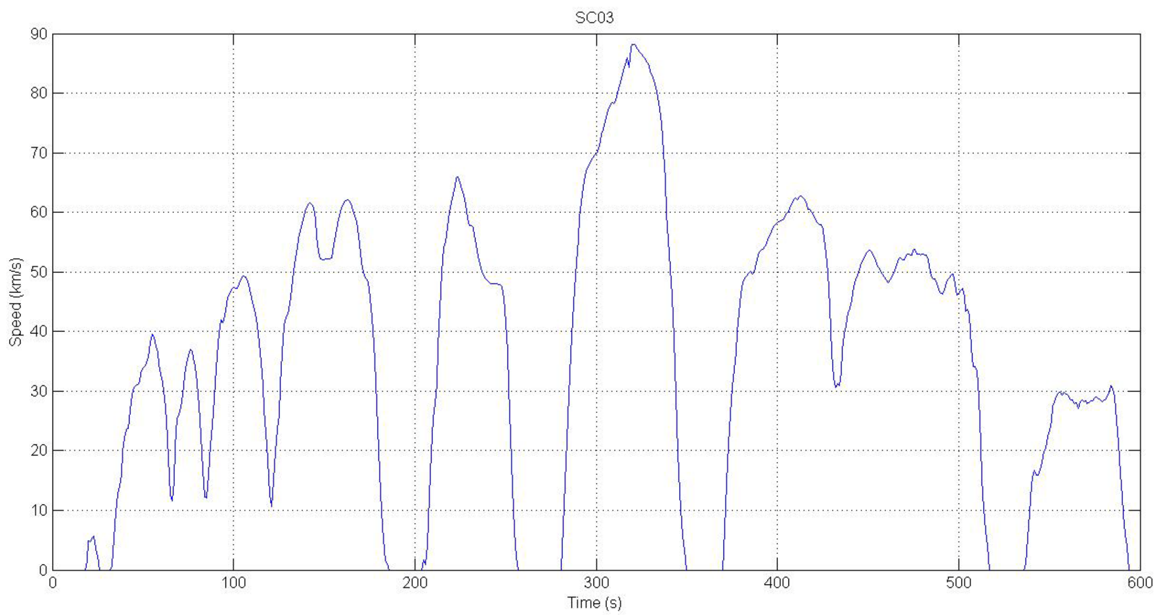


Figure C-5, EPA SC06

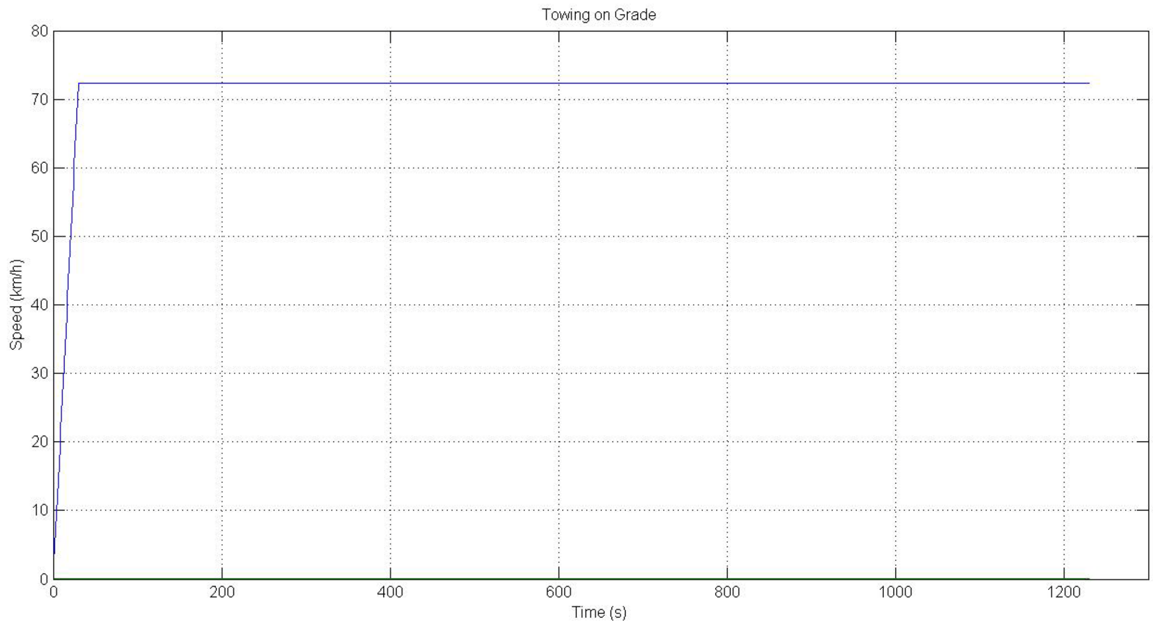
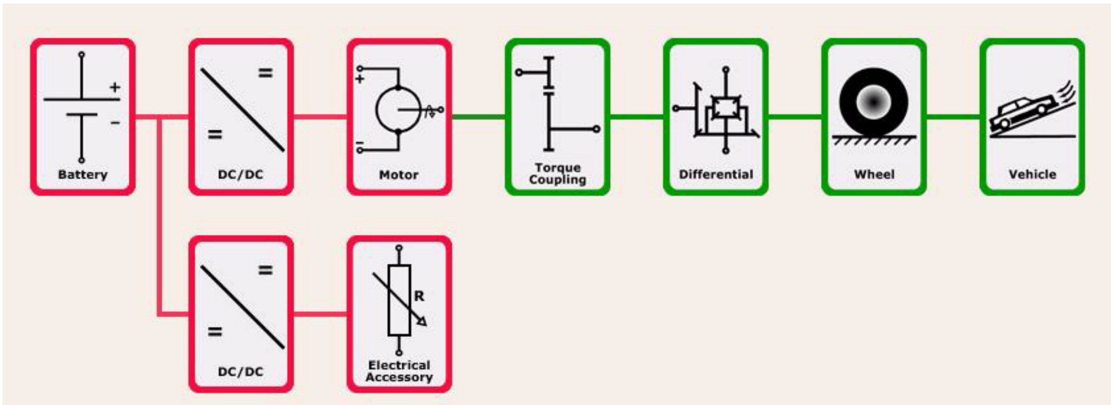


Figure C-6, Towing on 3.5% grade

Appendix D. PSAT Input

PSAT Input for major drivetrain components of 2009 Saturn Vue EV



Battery pack:

Technology = Li-poly
Initial SOC = 100%
Max SOC = 100%
Min SOC = 10%
Number of cell in series = 90
Number of module in parallel = 1
Nom cell V = 3.7 V
Max cell V = 2.7 V
Min cell V = 4.2 V
Max cell capacity = 240 Ah
Packaging factor = 1.2

Electric Motor:

Peak torque = 180 Nm
Continuous power = 40 kW
Peak power = 103 kW
Max speed = 12,000 rpm
Overall gear ratio = 10.946

Vehicle:

Total vehicle mass = 2130 kg
Transmission = single speed reduction
Frontal Area = 2.641 m^2
Drag Coefficient = 0.376

Tire:

Driving wheel = FWD
Tire size = P235 65 R16
Coefficient of rolling resistance 1 = 0.0068
Coefficient of rolling resistance 2 = 0.00012

Accessory:

Constant accessory load = 500 W