

The eBox: A New EV with Li Ion Battery and V2G

TOM GAGE
President and CEO
AC Propulsion, Inc.
441 Borrego Court
San Dimas, CA 91773
909 592-5399

Abstract

AC Propulsion has begun deliveries of the eBox, new full-function electric vehicle conversion. The eBox is built from the Scion xB, by replacing the gasoline engine and related systems with a 120 kW electric propulsion system and 35 kWh li ion battery. The eBox is not a hybrid. It is a pure battery electric vehicle with 240 km (150 mile) range, 0-100 km/hr (0-62 mph) acceleration in 7.2 seconds, and top speed of 155 km/hr (95 mph). The eBox has an integrated onboard charger with bi-directional power flow. The charger supports charge or discharge currents, at the grid frequency and voltage, at power levels up to 20 kW. The first production eBox was delivered in February, 2007.

The decision to produce the eBox was influenced by technology developments and market opportunities. The development of the eBox included vehicle selection, battery design, component packaging, and user interface design. The production process includes disassembly of the base vehicle, manufacture and installation of the battery enclosure, drive system and battery, and final assembly and test.

The eBox market includes two distinct segments, high-income early adopters, and utility and other research fleet operators that want to develop infrastructure for plug-in vehicles and vehicle-to-grid (V2G).

Keywords: conversion, eBox, electric vehicle, li ion, vehicle to grid,

1. Getting EVs to Market

In April 1990, General Motors announced its intention to produce an all electric car for sale to the public. Four months later, the California Air Resources Board announced a new regulation, the ZEV mandate that required other automakers, as well as GM, to produce zero emission vehicles (ZEVs) for sale in California. Then as now, only electric-powered vehicles qualified as ZEVs, so with one EV on the way, and many others required, the future of electric propulsion in cars looked good.

Ten percent share of light vehicle sales would have meant 150,000 new ZEVs on the road every year starting in 2003 in California. As it turned out, a total of about 5,000 EVs were placed in service by automakers from 1997 through 2003 and that was it. In 2007, automakers offered zero ZEVs to the market. So, seventeen years after GM introduced its EV amid great hope and fanfare at the Los Angeles Auto Show, the movement to electric propulsion that once seemed so promising has stalled totally. Why? Electric cars are victims of indifference on the part of the public according to the automakers. If you ask EV enthusiasts, they may tell you malevolence on the part of the automakers is the culprit. Chris Paine's excellent feature-length documentary film asks *Who Killed the Electric Car?* [1], and finds many parties guilty. But is the EV really dead?

We need electric cars now more than we did in 1990. Then, air quality was the only concern. Now add greenhouse gases and energy security to the reasons we need to substitute electricity for gasoline. Then, performance, price, and perceptions were all factors that worked against the EV. Now, battery progress

has improved performance, new economic models combined with cheaper, longer lasting batteries promise to moderate price, and policymakers as well as the car-buying public, battered by concerns about gas prices, climate, and foreign wars are looking anew at energy alternatives.

This paper explains why the EV really isn't dead and describes how one EV, the eBox, is designed to jump start EV commercialization by taking the first important step - putting real EVs back on the market.

2. Performance, Price, Perception

Electric vehicles have been burdened with marketing challenges that hinder their acceptance among new car buyers. These challenges can be categorized into performance, price and perception. They overlap to some degree but in general, any potential buyer of an EV will have concerns that fall into one of these categories. Performance and price can be improved through technology advancements and the improvements can be directly quantified. Perceptions are more difficult to measure and perhaps even harder to change. Only when perceptions match performance and price will the potential buyer become an actual buyer.

2.1 Performance

Electric vehicle performance - acceleration, top speed, and range - has improved greatly since 1990, although the improvements that have been demonstrated have not always been embodied in the EVs brought to market. This has been due in some cases to conservatism on the part of automakers and in other cases by economic and technical practicalities. The capabilities of various cars built by AC Propulsion are shown below in Table 1.

Table 1: Performance Trends in Electric Vehicles Powered By AC Propulsion

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Acceleration 0-60 mph sec		Impact ¹ PbA 8.5 sec			Civic PbA 6.2 sec				tzero PbA 4.2 sec					tzero Li Ion 3.6 sec				Wrightspeed X1 ² 3.1 sec
Top Speed mph					Civic PbA 85 mph				White Lightning racecar ³ NiMH 254 mph					tzero Li Ion 103 mph				eBox ⁴ Li Ion 115 mph
Range miles					Civic PbA 4-seat 85 miles				Golf NiMH 4-seat 130 miles					tzero Li Ion 2-seat 300 miles				eBox Li Ion 5-seat 150 miles

¹ Alan Cocconi designed drive system

² modified AC 150 drive system

³ two AC150 drive systems

⁴ special gearing

The trends are quite clear and result primarily from improvements in both battery power and battery weight, and also from better understanding of vehicle integration and high power electronics. These performance capabilities cannot necessarily coexist in the same car, but they do give the EV engineers a range of vehicle attributes that can be tailored to specific market segments. They allow EV product planners to package performance in ways that cater to buyer preferences.

2.2 Price

Electric vehicle prices are high because production volumes are low and batteries are costly. The low production volume means not only that economies of scale in manufacturing are lacking, but also that the costs of the intensive R&D necessary to bring whole new technologies to market are spread over a small number of vehicles. The most appalling case in point is perhaps the General Motors EV1. Development and tooling costs as high as \$360 million have been reported by GM. Spread over EV1 production of 800 units gives an investment allocation of \$450,000 per car.

The EV1 along with most other EVs manufactured by OEMs were only leased, not sold on the open market. The benchmark for EV pricing is the Toyota RAV4 EV which was sold to the public by Toyota in 2002 and 2003 for a price of about \$45,000. When sales were announced, Toyota also gave an estimate for battery replacement cost of \$30,000, suggesting either that production cost of the EV w/o battery was very low, or that the price did not reflect actual costs. The latter is the more likely case and would not be an unusual situation. Automakers price high when the can, but must price low enough to clear the market which can mean pricing below cost in some cases. It is interesting to note that scarcity has driven up the price of used EVs. Some used RAV4 EVs now sell for well over \$50,000.

The eBox is sold as a conversion, \$15,000 for the car and \$55,000 for the conversion, \$70,000 in all. At that price it is beyond the reach of many who would like to own an EV, but well within the range paid for many new cars every year. Considering relative performance, a new eBox compares favorably to a used RAV4 EV.

It is helpful to consider battery costs separately from the cost of rest of the EV. In time, with volume, the EV without battery will almost certainly cost less to manufacture and warranty than a conventional car. For the battery, battery cost and life must be considered together. A battery that costs less and has a shorter life may be more economic even considering the inconvenience and cost of battery replacement. For this reason battery cost per mile is the best way to look at battery cost. This requires a clear understanding of the interplay between battery calendar life and battery cycle life. It also means that battery life is properly considered along with energy costs as an operating cost. An apples-to-apples comparison with a gasoline car then requires that operating costs for both types of cars should be considered.

For eBox customers we provide data like that shown in Table 2 to help them understand how operating costs will compare. The shaded squares indicate expected values for the eBox. Of course gasoline is only one of the operating costs for conventional cars.

Table 2: Energy Operating Cost: Electric vs. Gasoline

electricity ¢/mile				battery replacement ¢/mile				gasoline ¢/mile			
AC Wh/mi	electricity cost \$/kWh			batt life (000) mi	battery cost \$000			MPG	gasoline cost \$/gal		
	\$ 0.08	\$ 0.16	\$ 0.24		\$ 10	\$ 20	\$ 30		\$ 2.75	\$ 5.00	\$ 7.25
200	1.6	3.2	4.8	100	10	20	30	45	6.1	11.1	16.1
250	2.0	4.0	6.0	80	13	25	38	37	7.4	13.5	19.6
300	2.4	4.8	7.2	60	17	33	50	30	9.2	16.7	24.2
350	2.8	5.6	8.4	40	25	50	75	27	10.2	18.5	26.9
400	3.2	6.4	9.6	20	50	100	150	15	18.3	33.3	48.3

Clearly battery wearout cost more than offsets the savings from using electricity instead of gasoline. At the same time, EV operating costs including battery wearout are already in the same range as what some people who drive vehicles with low fuel economy pay today just for gasoline. For people who might

value driving an EV as much as others value driving a Hummer, the economic cost is affordable and acceptable.

Several factors are at work that may reduce the energy operating cost of the EV:

- In automotive volumes greater scale economies will further reduce cell manufacturing costs
- Large R&D efforts may extend the life of li-based cells operating in automotive environments
- Increases in drive system, vehicle, and tire efficiency will reduce energy consumption
- If EV drivers accept lower range, they can use a smaller less costly battery, so if the life remains the same, battery cost is reduced significantly (this will be discussed more in the section on Perceptions)
- Payments to drivers who allow their vehicle to be used in V2G service (see below) may amount to a net benefit of 10¢/mi to 20¢/mi, a significant effect on overall cost.

For gasoline cars, fuel economy improvements including hybridization will be offset to some extent by the likely ongoing rise in gas prices that result from both market forces and policy. When or if energy operating costs for gasoline cars and EVs will converge or even cross is uncertain. It is likely that the costs will become close enough and vehicle features different enough that for many buyers factors other than price will determine whether they buy an electric car or a gasoline car.

2.3 Perceptions

Two sets of perceptions affect attitudes toward EVs. One set involves the operating characteristics of EVs and includes perceptions that EVs do not perform as well as conventional cars in areas such as range, acceleration, speed, and refueling convenience. The second set relates to big picture issues such as perceptions that EVs may create electricity shortages, more pollution from generation, or hardship for people who don't have a place to plug in. Both sets of perceptions have some basis in reality but public debate has stirred uncertainty about EVs into apocalyptic fears. Some people worry that gasoline cars will be taken away from them. Others worry about what will happen if EVs gain 100% market share. Negative perceptions are fortified by these fears and became significant market barriers for EV commercialization.

Concern about driving range is a good example. For a gas car range is not an important issue, but the low energy density of batteries limits driving range for EVs. In opposing the ZEV mandate, automakers asserted their marketing wisdom that no car can be commercialized unless it operates just like a gas car. With that logic came the insistence that 300 mile range is a necessity for an EV. That led, in turn, to huge investments in advanced batteries for EVs. When the 300-mile battery proved elusive, attention turned to the "hydrogen economy" a fantastic vision for a totally new energy infrastructure. All because of the perception that ZEVs need 300 mile range.

Reality is often different from perceptions. It turned out that it was EV drivers who had their cars confiscated. EVs will never have 100% market share, that's not the worry. The worry is how to get up to 1% of market share. Improvements in battery technology have come from the computer industry, not from advanced automotive battery programs. And of course ZEVs do not need 300 mile range.

Technology need not improve any further for EV commercialization (although it will and that will help). But perceptions do need to change. More range is always nice, but people are learning that they can get by on 120 miles, or 90, or even 60 because they can charge while they are parked. Economic logic reinforces this perceptual change. If it takes \$100 in battery cost to buy one mile of range, 100 miles of range requires a \$10,000 battery. Triple that for 300 miles of range. When car buyers understand the economics they value range differently. They conclude that it does not make sense to buy and carry around in their car a big, expensive battery that they rarely use. They buy a smaller battery that meets

most of their needs and make other arrangements for long trips. People who often need 300 miles of range won't buy an electric car.

EVs will be commercialized not to the extent that batteries can approach 300 miles of range, but rather to the extent that buyer perceptions move away from the need for 300 mile range. The best way to alter perceptions is to let people learn for themselves or from word of mouth. That requires EVs on the roads.

3. The eBox concept

In 2003, The California Air Resources Board adopted changes to the ZEV Mandate that allowed automakers to satisfy regulatory requirements by building just a few fuel cell cars. As a result, automakers dropped their plans to produce more electric cars, stopped selling the ones they had, and started gathering back and taking out of service many of the EVs they had leased. This left a pool of frustrated and deprived former EV drivers, EV fleet managers who were running out of EVs, and EV intenders who wanted to buy but learned that they were too late. The ZEV mandate had brought OEMs into the market with (some) well-engineered EVs. Under pressure from the mandate, they offered these EVs at subsidized prices that prevented small companies such as AC Propulsion from competing. When the OEMs then dropped out of the market, no other EVs were available. Access to EVs was effectively denied.

Without OEMs in the market, a new opportunity for low volume EV production opened up. Many companies saw opportunity where the OEMs saw threat, and began planning to build EVs without OEMs. AC Propulsion developed a Plan for Production of Electric Vehicles. Our plan took shape during late 2003 as we considered how to produce EVs, for whom, and with what hardware. Our plan proceeded, though not without delays, and we drove the first eBox on June 24, 2006. That was the same day *Who Killed the Electric Car?* premiered in Los Angeles.

3.1 Conversion vs. ground-up

Ground-up construction, or clean-sheet design is the best way to build an electric car because it allows the engineer to accommodate the batteries, the biggest, most expensive, and most important part of an EV, in the most effective way. But as we had learned building three of our tzero electric sports cars [2] ground-up design requires huge effort just to design and build standard components like doors, windows, and lights, let alone the important aspects that differentiate EVs from conventional cars.

AC Propulsion also new from building conversions of gasoline cars like Honda Civics and Volkswagen Golfs, that finding space for 500 kg of battery in a compact car platform and maintaining good balance for handling, steering, and braking is also a big challenge. Our first Civic conversion [3] has driven every one of its 138,000 miles carrying 28 lead acid batteries of 20 kg each and weighing in at well over Honda's gross vehicle weight rating for the car. Although no suspension or bearing problems have occurred with that car, we know that it does not handle as well as the original Civic, or as well as we would have liked. OEM EVs had raised the bar in some ways, including vehicle balance and integration, and we wanted to continue improving EV acceptability.

In 2003, we converted our tzero from lead acid batteries to li ion batteries and the result was a revelation [4]. The li Ion tzero was 500 pounds lighter, it had the same power and four times the range. Without doing anything to the drive system or chassis, 0-60 mph time went from 4.1 sec to 3.6 seconds, it handled better, and gained an inch of ground clearance. It was the lightness. The high specific energy of the li ion battery meant that battery weight would no longer overwhelm the chassis of a converted car. The direction of our plan became obvious. We would produce electric cars by converting gasoline cars using li ion batteries.

3.2 Target markets: fleets and early adopters

The OEMs had sprinkled several thousand EVs around California and in a few other states. They included two pickup trucks, two minivans, a small sport utility, a 3-door hatchback, and a 2-seat coupe. Those vehicles and their drivers gave us some insight into what people wanted, needed, liked and disliked in those EVs. We also could see that the biggest users of EVs were fleets, especially municipal and electric utility fleets. They had motivation and either discretionary budget or access to subsidies that allowed usually tight-fisted fleet managers to pay the EV price premium. In the non-fleet sector, the EV1 was the favorite for its technological sleekness and performance, but even EV1 champions sometimes regretted its limited seating capacity, if only because it meant they could show off to only one passenger at a time.

The RAV4 EV was a favorite of fleets, and after Toyota made it available for sale, it became a favorite of the individual users as well. Its practicality, relatively good efficiency and range, and as it developed, its unmatched durability and reliability, not to mention the very fact of its availability, have earned it the consensus best EV from the OEM era.

We decided that the AC Propulsion EV would have to appeal to both fleets and individuals in order to maximize its marketability. It would have to take advantage of the lithium battery we planned to use to optimize its appeal, it would have to offer high utility for fleet use, and an agreeable and fun driving experience for everyone. We wanted it to be better than the RAV4 EV in every way it could be.

3.4 Choice of platform

We knew that our EV would be expensive but we did not know whether that meant, 1) we should load the cars up because the buyers would have to be so wealthy in the first place that price would not be a factor, or, 2) the battery and drive system are so expensive that we should economize on everything else in the car to keep the cost down. We conducted surveys in 2003 and the results suggested that many EV prospects would pay extra for an EV even if they had to stretch their budget somewhat. Although they were used to the amenities in their cars, they would buy an EV based on its EV performance, more than on other features and attractions. We decided to build an EV that would appeal to a broad range of users and that could compete against other EVs by providing the best EV features at the lowest price. To keep control of costs we needed a donor platform that had low initial cost and that could be converted without unnecessary complexity.

We also knew that vehicle efficiency is extra important for an EV because it does more than reduce fuel cost. In an EV, the customer value of efficiency is compounded because it increases range and charging rate as well. Range bought with efficiency is usually cheaper than range bought with battery cost, so we wanted to start with a platform that was as efficient as possible. Fuel economy ratings are indicative of efficiency but are affected significantly by powertrain efficiency. We would be discarding the powertrain, so weight and aerodynamics became the prime considerations. Aerodynamic drag is less important at the lower average speeds encountered in local driving, and drag data for many vehicles are not available, so we used vehicle weight as the best first order indicator of platform efficiency.

We developed a table of comparative data for 2003 models sold in the US that were in or near the compact size class. We multiplied price by weight to derive an indicator of EV platform suitability, as displayed in Figure 1.

The Scion xA and xB, both new for 2004 model year, were near the top of the chart. They are built by Toyota and marketed as a youthful, exuberant brand. The base price includes features and accessories that cost extra in most low-price cars. Comparing the xA and xB to their neighbors on the chart on factors such as style, fun, equipment levels, and quality, the two Scions were a clear choice. Although the xA

and xB are built on the same platform, the xB has 130 mm more wheelbase than the xA. That extra length proved critical for battery packaging so we chose the xB as the base platform for our EV

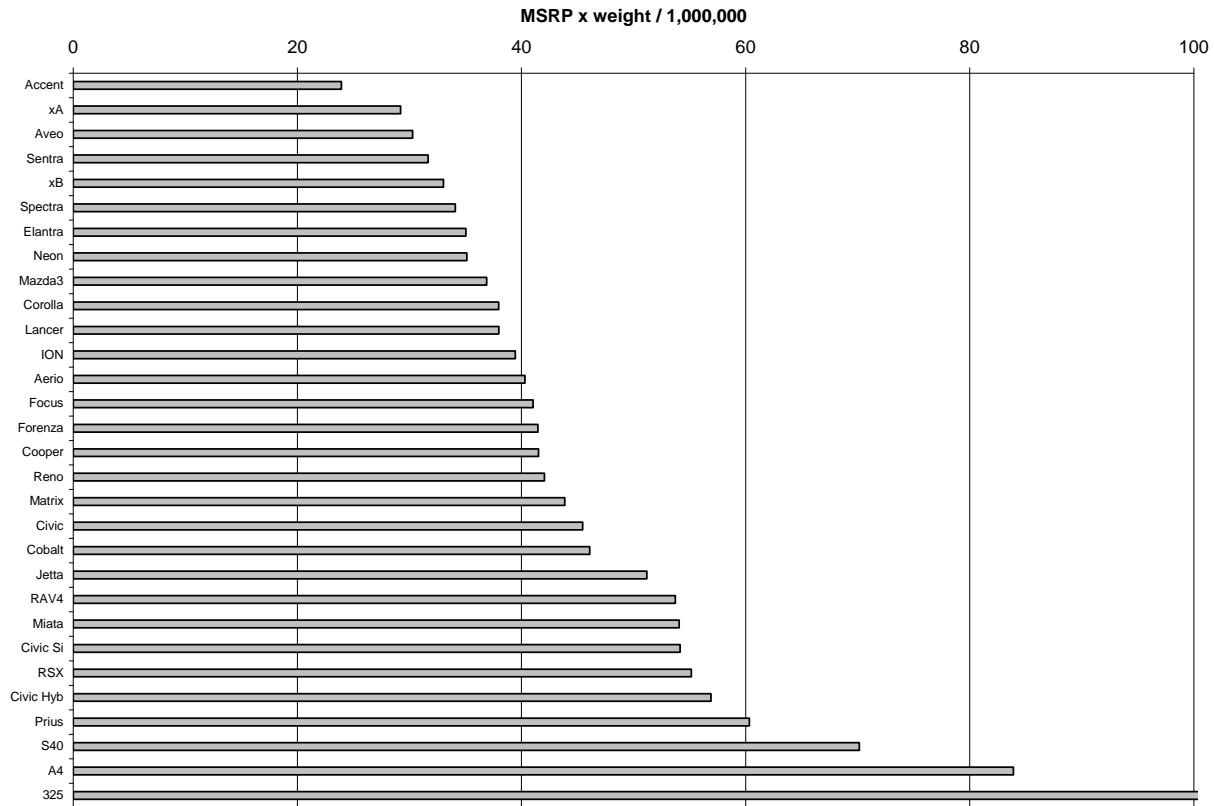


Figure 1: 2003 models compared on price times weight

conversion. We did so understanding that the xB did not fully meet the criteria of high efficiency where aerodynamics are concerned, and we accepted that energy consumption at highway speeds would be compromised somewhat. Once we chose the xB, the name for our new EV was obvious. We would call it the eBox.

4. eBox Vehicle Integration

Conversion of the Scion xB into the eBox involves integration of three major systems into the vehicle, the power system, the battery, and the driver interface. Compared to earlier EV conversion programs at AC Propulsion in which only a few prototypes were produced, the eBox program involved development for low-volume production. Extra attention was given to developing the conversion components and systems so they could be produced and installed easily and repeatably.

4.1 Power system

The eBox uses AC Propulsion's standard drive system adapted to the intended mission of the eBox. This meant reducing peak power from 150 kW to 120 kW in line with the limited performance envelope of the front wheel drive chassis and original equipment tires. The AC150 is an integrated power system that includes an AC induction motor, inverter, charger and 12V power supply. The charger employs a patented design that uses inverter IGBTs and motor windings as elements of the charger. This dual function design provides 20 kW of charge power and eliminates the cost size and weight of a separate charger [5]. The inverter, charger, and power supply are packaged in a single enclosure called the Power Electronics Unit

(PEU) that resides under the hood in the area formerly occupied by the top half of the internal combustion engine.

The traction motor is a four-pole induction, high-frequency, copper rotor design providing high specific power, high energy efficiency, and inherent safety. The motor provides a broad range of high-efficiency operation with a base speed of 5000 rpm and an rpm limit of 13,300 rpm. This allows a high torque multiplication in the gearbox still with top speed suitable for freeway driving in California. The motor is mounted directly to the fixed-ratio gearbox. The gearbox uses the original 5-speed case and differential mounted in original location but fitted with a new input shaft and counter gear giving 8.84:1 overall gear ratio.

Drive for the power steering hydraulic pump and A/C compressor is provided by belt drive from a separate accessory drive motor that operates at a fixed speed when the ignition is on. The power steering and A/C system are not modified. Other accessories include a 12V vacuum pump for brake boost and an electric 4-kW coolant heater that circulates heated coolant through the original heater core for defrost and cabin heat. The entire power system except for the PEU is assembled onto the front chassis cradle before installation into the vehicle, Figure 2.

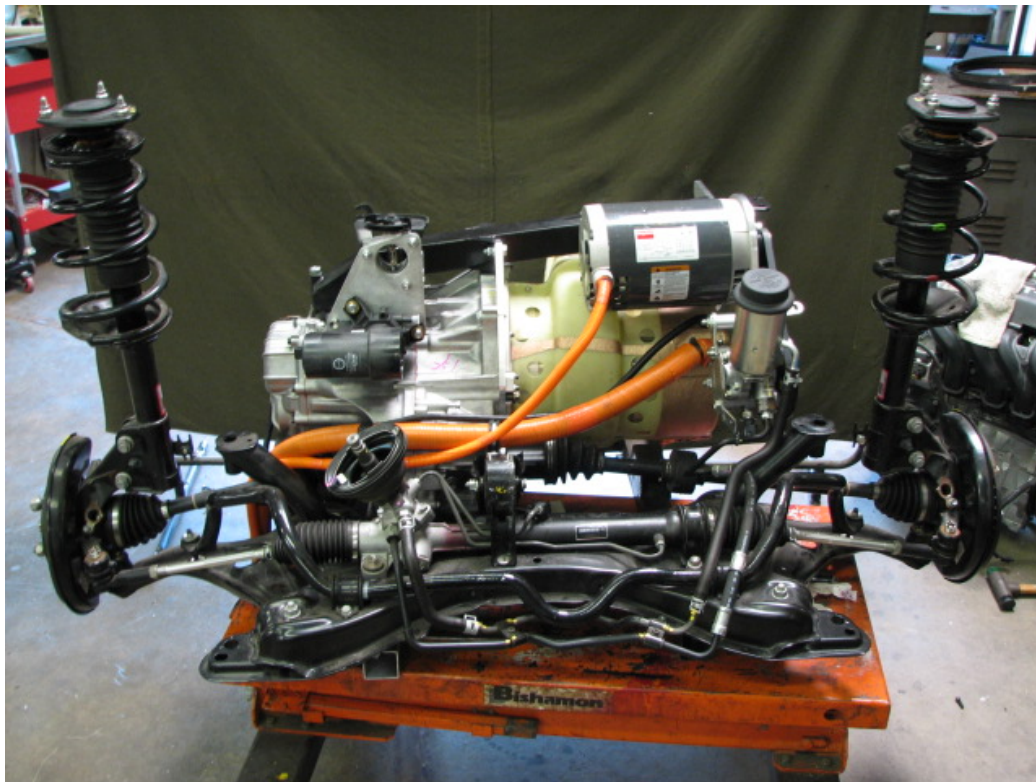


Figure 2: The eBox power system

4.2 Battery

The eBox uses a battery assembled from 5,088 small li ion cells. The cell size designation is 18650, the same size used in batteries for laptop computers, as shown in Figure 3. The 18650 cell is produced in a wide range of variations that give specific energy ranging from 90 Wh/kg to well over 220 Wh/kg. Most 18650 cells are manufactured in Asia with monthly production totaling over 250 million cells. Cell prices yield a specific cost at the cell level under \$300/kWh. For both specific energy and specific cost, 18650 cells are highly attractive, even considering assembly cost, compared to larger cells produced in lower volume for automotive applications.



Figure 3: 18650 cell (left), AA cell (right)

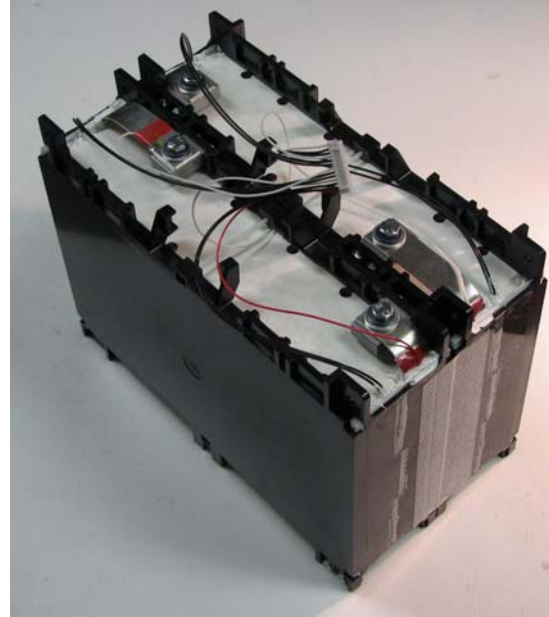


Figure 4: 53P4S module

Assembly of small cells into large batteries uses techniques similar to those used to produce smaller batteries for portable equipment. Cells are connected in parallel to achieve ampere-hour capacity requirements, and those parallel groups are connected in series to achieve requisite voltage. In the eBox, the cells are assembled into blocks of 53 parallel cells. Four such blocks are connected in series to create a 53P4S module rated at 106 Ah and 14.8 V, Figure 4. The eBox uses 24 modules connected in series.

Li ion batteries require monitoring at the cell level to strictly maintain cell voltage within limits. Temperature limits must also be observed carefully to enhance cell life and avoid cell failures. Accordingly each module in the eBox includes a battery monitor that measures four voltages and four temperatures and transmits the measurements to a vehicle management system (VMS). The VMS controls charge and discharge functions of the drive system to maintain battery cell voltage and temperature within approved limits. If one or more cells approach preset limits the VMS provides audible warning to the driver, then ramps down operating power, and finally shuts down the drive system. This level of autonomous control avoids operation in regimes that could cause cell damage or failure.

In the eBox, the modules are assembled in two boxes that support them and provide flow area for forced air cooling, see Figure 6.

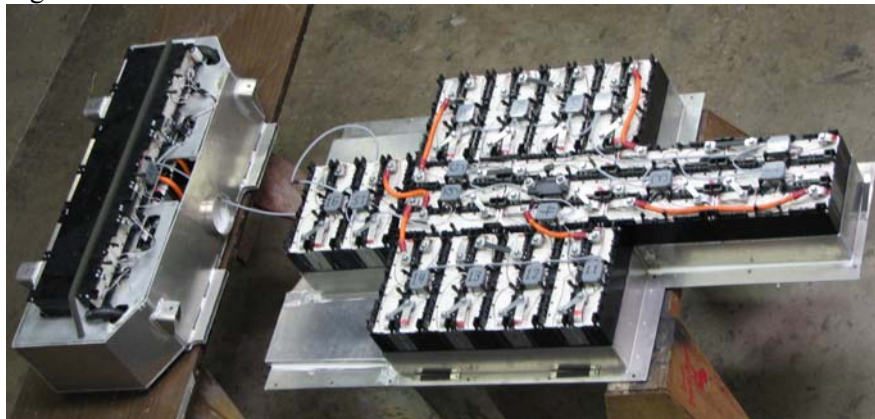


Figure 6: The eBox battery

The battery boxes bolt into enclosures under the vehicle floor, one under the tunnel and front seats, the other under the rear seat where the fuel tank had been located. When installed in the car, the battery boxes are sealed to prevent leakage of cooling air from the intended flow paths. The cooling air can be refrigerated by the HVAC system.

4.3 Driver Interface

In most ways EVs drive the same as conventional cars, but there are important differences and good EV design allows the driver to take advantage of these differences for both increased functionality and driving pleasure. The eBox driver interface includes system controls and instrumentation that allow the driver to enjoy electric propulsion and get the most out of it.

Regenerative braking differentiates the EV (and hybrid) from the conventional car in that it can allow the car to decelerate sharply without using the conventional friction brakes. The traction motor reverses torque and is driven by the vehicle instead of vice versa. The kinetic energy of the moving vehicle is converted to electricity that partially restores charge into the battery, and the car slows down. In the eBox, control of regenerative braking is entirely on the accelerator pedal, it is not blended with the conventional brakes at all. This division of braking control between motor braking (regen) on the accelerator pedal and friction braking on the brake pedal clearly differentiates the two kinds of braking and allows the driver to maximize energy recovery for best efficiency and minimize wasteful use of friction brakes. Practiced drivers can, if they choose, drive without ever using the brake pedal, even in heavy traffic. The friction brakes remain available at any time if they are needed for a sudden stop.

Some drivers may prefer a more even mixture of braking function. The eBox allows this with a regen control lever that sets the level of regen, Figure 7. With less regen, the cars slows upon release of the accelerator pedal, but more like a conventional car. Use of the brake pedal is required for normal driving. An indicator above the regen control shows brake light status to reassure the driver that the brake lights illuminate while decelerating even though the brake pedal is not used.

Some EV drivers like to have access to a lot of information about the operation of their car, but others, especially inexperienced EV drivers, can be intimidated or irritated by complex controls and instrumentation. The instrumentation for the eBox is intended to satisfy both types of drivers. The standard instrument cluster is modified to make the tachometer read as an ammeter for both discharge and regen, Figure 8. The fuel gage is modified to give an analog indication of remaining battery charge, The algorithm compensates for current levels so that the indication is not unduly distorted by short term variations in speed, acceleration, or grade. The tapering graphic on the fuel gage provides a visual reminder that performance declines somewhat with battery state of charge.



Figure 7: Regen control lever



Figure 8: eBox instrument cluster

In addition to the analog cluster, the eBox is equipped with a graphic display located on the steering column directly in view of the driver, Figure 9. The display uses multiple driver-selectable screens to give the driver detailed information about vehicle systems and to provide a control interface that allows the driver to set preferences such as metric or US units, charging time or rate, V2G requirements and other functional variables.

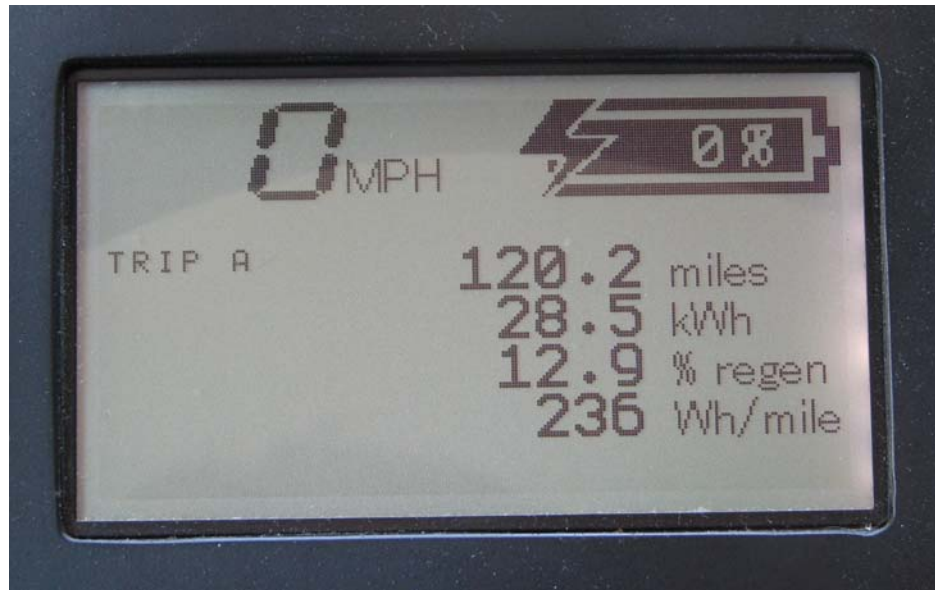


Figure 9: Driver display screen

The driver display screen is navigated by a control knob located on the center console.

The eBox requires no shifting and reverse is engaged by reversing the rotation of the traction motor, so a conventional shifter is not required. An electric switch is all that is needed, so the space and weight of a shift lever can be eliminated. To allow garage shifts, engaging forward or reverse conveniently while rolling slowly, the eBox has a low-travel selector stalk for forward, neutral, and reverse mounted on the display screen housing near the steering wheel.

5. eBox Performance

Electric cars ultimately have to compete with conventional cars for buyers, and as market perceptions shift, the acceptance of limited function EVs such as NEVs (under 25 mph) and city EVs (under 60 mph) will increase as their functionality and benefits become better understood. In the near term, to help shift market perceptions as well as to attract buyers, it is important to demonstrate full function EVs that deliver a superior driving experience. In the eBox, the AC150 power system and lithium battery combine to accomplish this.

5.1 Driving

In track tests, the eBox accelerates faster, handles better, and is quieter than the Scion xB from which it is built, Figure 10 [6]. At the same time it uses less energy, and emits less pollution. First-time drivers frequently comment how smooth and powerful it is. Back-to-back drives in an eBox and a Scion xB reveal that the character of the two vehicles is completely different. The eBox, without the noise and vibration of the small 4-cylinder engine, drives more like a V8-powered car. This is not to criticize the xB, but rather to say that the xB platform is transformed with electric propulsion. While driving an eBox on a short route with three passengers onboard, the Scion's vice-president said, "I like it...I love it".



Figure 10: eBox at the test track

Besides vehicle dynamics, the other important aspect of EV driving performance is efficiency. With a curb weight of 1350 kg, the eBox returns excellent efficiency despite its boxy profile. Energy consumption in urban driving is 125 Wh/km. On the highway at 100 km/hr, consumption is 160 Wh/km. In typical driving in the Los Angeles area which includes a good portion of freeway driving, the eBox operates at between 140 and 190 Wh/km and this yields driving range of 185 km to 250 km using 100% of battery capacity.

5.2 Charging

The onboard 20 kW charger allows the eBox to charge from empty to 100% in a minimum of about 3 hours. In actual use, EVs are rarely discharged fully, and normally are charged to full overnight when charge time is not critical. The real benefit of the high-power charger, and of the eBox's efficient use of energy is the rate of range recovery. Charging at 20 kW, the eBox can recover 50 km of range in less than 30 minutes. This will be an important feature in future EVs because as charging infrastructure becomes more widespread, the ability to restore range during short stops can greatly extend the daily driving range of an EV even as the battery size is reduced to save cost. In the near term, before charging infrastructure is fully developed, the eBox is able to charge from any single-phase outlet whether 110V, 208V or 240V. The eBox can be manually set to any line current available from 1A to 80A and thus take advantage of the maximum charge power available.

5.3 Vehicle to grid

The concept of vehicle to grid, or V2G, considers the potential for vehicles that plug in to the grid to provide beneficial interactions with the grid. V2G has been studied for at least ten years and two 2005 papers give thorough treatment to V2G fundamentals and implementation [7], [8]. Over this time, several factors, including the growth of home solar power, the energy market manipulations of 2000/2001, and growing awareness of V2G research have increased the level of interest in V2G at major utilities including PG&E, PHI, Austin Energy, and LADWP. Field evaluations of V2G have been limited due to the scarcity of vehicles capable of plugging in and responding to grid control commands.

The eBox is fully V2G capable. It is built with the same hardware capabilities as the AC Propulsion converted VW "Plug Bug" that was used in a CARB-sponsored study of V2G in 2002 [9]. That study demonstrated vehicular response to power dispatch commands from the grid operator, and showed that the response and capacity of the vehicle were sufficient to generate significant revenue based on real market pricing for grid ancillary services. The key to revenue generation is the ability to respond to grid commands with sufficient power (>10 kW), and the ability to source as well as sink power. The bidirectional power flow is essential to the ability to supply ancillary services whenever the car is plugged in.

7. Conclusions

Electric vehicle technology continues to improve and is capable of providing excellent operating characteristics and establishing new roles for vehicles as elements of the power grid. Economics continue to be a challenge but downward trends in component costs, potential for revenue from V2G, and increasing costs for conventional vehicles and fuels are favorable for electric propulsion. Market perceptions may be the biggest barrier to broader commercialization of EVs. New companies with new EVs that demonstrate the functional as well as sensual appeal of electric transportation will fill in the void left when OEMs abandoned the EV market, and continue to change people's perceptions. The eBox offers an example of the progress that has been made and what can be expected in the future, Figure 10.



RAV4 EV		eBox
26 kWh	Battery capacity	35 kWh
60 kW	Power	120 kW
1590 kg	Weight	1350 kg
145 km	Range (100 km/hr)	220 km
~15 sec	0-100 km/hr sec	7.2 sec
125 km/hr	Top speed	155 km/hr
180 Wh/km	Energy use (100 km/hr)	160 Wh/km
Offboard / 6 kW max	Charger type / power	Onboard / 20 kW max
30 km/hr	Charge rate	125 km/hr
Charge only	Vehicle to grid	Bi-directional

Fig 10: Specifications and performance data for eBox and RAV4 EV

8. References

- [1] Chris Paine, Jesse Deeter. *Who Killed the Electric Car?*. Sony Pictures Classics, New York, NY, 2006.
- [2] Alec Brooks, Tom Gage. *The tzero Electric Sports Car – How Electric vehicles Can Achieve Both High Performance and High Efficiency*. EVS17 Symposium Proceedings, Montreal, Canada, October, 2000.
- [3] Tom Gage. *Living With an EV: 30,000 Miles in One Year*. EVS13 Symposium Proceedings, Osaka, Japan, October, 1996.
- [4] Chris Dixon. *Lots of Zoom, With Batteries*. New York Times, New York, NY, September 19, 2003.
- [5] William Korthof. *Level 2+: Economical Fast Charging for EVs*. EVS17 Symposium Proceedings, Montreal, Canada, October, 2000.

- [6] Mark Vaughn. *Electricity is in the Air, and in the eBox electric car*. AutoWeek, Detroit, MI, April 19, 2007.
- [7] Willett Kempton, Jasna Tomić. *Vehicle to Grid Fundamentals: Calculating Capacity and Net Revenue*. J. Power Sources Volume 144, Issue 1, Pages 268-279, 1 June 2005.
- [8] Willett Kempton, Jasna Tomić. *Vehicle to Grid Implementation: From stabilizing the grid to supporting large-scale use of renewable energy*. J. Power Sources Volume 144, Issue 1, Pages 280-294, 1 June 2005.
- [9] Alec Brooks. *Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle*. Final Report, Contract number 01-313, California Air Resources Board, Sacramento, CA, December, 2002.

9. Author



Tom Gage
President and CEO, AC Propulsion, Inc.
Phone: 909-592-5399, Fax 909-394-4598, email: tgage@acpropulsion.com
BSME Stanford University
MBA Carnegie Mellon University
1984 to 1992 Product Planning and Regulatory Strategy Office, Chrysler Corporation
1996 to present, AC Propulsion, Inc.