

MASS REDUCTION AND PERFORMANCE OF PEV AND PHEV VEHICLES

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U.S.A.

Paper Number 11-0346

ABSTRACT

Within the context of the U.S. government's recent announcement on fuel economy standards for 2017 to 2025 model year vehicles, automakers are looking to next generation hybrids, plug-in electrics and even fuel cells. When looking at these next generation vehicles, weight reduction technology cannot be overlooked. Complementing vehicle advances, lightweighting produces vehicles that are more efficient, achieve better fuel economy and produce fewer emissions. Proven in strength and safety, aluminum offers automakers the key to vehicle weight reduction. Research findings pertaining to the impact of weight reduction through lightweight materials on plug-in electric and hybrid vehicle performance, show that opting for aluminum bodies over steel can save on battery needs and the associated higher costs, since lighter vehicles require less battery power (batteries being a significant cost barrier). Greater use of aluminum can help speed the transition to greener and cleaner vehicles.

Areas of focus

- Electric vehicles (EV) or plug-in hybrid electric vehicles (PHEV) as a unique class of vehicle(s) in that they contain a relatively small amount of stored energy, and as such are great candidates for lightweighting;
- The role of vehicle, battery and powertrain mass, as well as drive cycle on range and performance;
- Potential cost-savings by upgrading from traditional steel to an advanced aluminum body structure due to lower energy requirements to move lighter vehicles.
- The function of vehicle mass and its influence on energy recovered during regenerative braking.

Key Findings

- A savings of up to \$3,000 can be reached by reducing electric vehicle structure weight by 10 percent with aluminum.
- Using aluminum in select automotive components could reduce vehicle weight safely by as much as an additional 40 percent over today's vehicles.
- An additional 525 pounds (including primary and secondary weight) safely could be taken out of a

- vehicle by 2020, which would result in saving 2.7 MPG, a nearly 10% fuel economy improvement.
- Reducing vehicle weight will be vital to improving fuel economy and cutting carbon emissions.

Not all cars will or should be made of aluminum (though some are, and more will be); however, it is clear that aluminum components will continue to provide vehicles that are safe for consumers and the environment.

INTRODUCTION

In previous studies with Ricardo and IBIS, fuel economy versus weight versus engine (type or displacement) versus vehicle type (car or SUV) versus manufacturing cost versus LCA has been examined. In all cases, a very positive synergy was found between primary and secondary weight reduction, engine displacement and cost. Less weight = smaller engine = better fuel consumption = better economic LCA. Usually, 2-4 years of driving were required to recover the upfront investment. Aluminum lightweight structures have real long term value. The barriers are the up front costs (investment, knowledge) by the OEM, and having the customer value the operational costs versus initial purchase price.

With the growing popularity, or interest, in PEVs (plug-in battery powered electric vehicles) or PHEVs (plug-in hybrid electric vehicles) it was desired that a more complete examination of weight versus electric motor size versus battery versus cost be completed. It was anticipated that these vehicles would be good candidates for lightweight structures since the battery pack contains a relatively small amount of energy that must be well managed.

In this study, all vehicles will perform using only the battery pack and electric motor. However, the PHEV is still considered, since the range extending ICE in these vehicles must be considered as additional mass when the vehicle is operating only as an EV (the first 40 miles or so) and is an additional cost to consider in the overall economics, which will be a topic of a future study.

All vehicles used lithium ion batteries. These batteries are attractive because they have relatively high specific energy and power densities, and adequate volumetric energy densities, and charge/discharge rates; but, they are relatively expensive and in some applications have a history of thermal run away. Significant research and development is being applied to battery development, so rather rapid advances in battery capacity, manufacturing and cost reduction are anticipated or claimed.

No specific mention of battery chemistry will be noted in this report, other than to comment that there are a broad range of anode and cathode chemistries with a corresponding broad range of claims for capacity or cost. For this study, we believe we have picked generally accepted, nominal values for battery packs associated with vehicles. Certainly better, albeit generally smaller or single purpose battery claims can be found. Battery packs for vehicles are essentially an assembly of smaller individual batteries or cells and for reasons of balancing out the various cells and managing the thermal discharge of the pack; the pack is designed to operate in a more conservative mode than that of the individual cells. Further, battery packs are somewhat customized for EV or PHEV applications; but, we assumed a common battery pack in the current study.

Background and Assumptions

In this study, based on publicly available info, some private discussions with battery makers, and some information Ricardo had from their previous government studies, we assume a useable specific energy of 115 W-h/kg with a specific volume of 155 W-h/l. We assume a state of charge (SOC) of 0.9 - 0.25 of the rated energy (starting and ending voltage that could be routinely used without damaging the battery). The price for the battery pack is estimated at \$750/kWh. This number is based on some public disclosures and private discussions. Costs in the range of \$500/kWh to \$1,000/kWh can be found. This rather broad range of costs reflects the rate of anticipated development and promotional pricing, as well as the completeness of the battery pack. Is all the associated structure included, including the thermal management requirements? This makes estimating the total battery weight quite difficult. From published values, the Tesla battery pack (52 kWh/450kg) has a density of 0.115 kWh/kg, while the Volt battery pack (16kWh/170kg) has a density of 0.094kWh/kg.

Existing PEV vehicles

The most acclaimed of the current PHEV vehicles is the Chevy Volt. The Volt has a 16 kWh Li-Ion (220 cell) battery pack, with a 111 kW electric drive. It has a 53kW ICE-generator to extend the range. While the vehicle mass has not been reported, a conventional steel vehicle with the same footprint would weigh about 1,384 kg (3050 lbs) and the BIW would weigh approximately 249 kg (549 lbs). The Volt achieves a 40 mile range based on the EPA city drive cycle (FTP75) and has a top speed of 100 mph. The reported SOC is 0.85-0.3 which gives a usable energy of 8.8 kWh. The reported mass of the battery pack is 170 kg (375 lbs).

Another point of reference is the Tesla Roadster. This production vehicle is an aluminum structured vehicle with a curb weight of 1,221 kg. It has a motor of 165 kW, powered from a Lithium-Ion battery pack of 53 kWh with an excellent sporty performance and a range (EPA combined city/highway) of 244 miles. The battery contains about 6,800 cells grouped into 11 modules and is fluid cooled with a weight of 450 kg. The battery is about 37 percent of the total vehicle curb weight. It has been suggested that Tesla's next generation midsized vehicle would have a 70 kWh battery pack, but this number has not been confirmed.

Regenerative braking is generally applied to PEVs, although specific details are not known. For our study the regenerative-braking threshold was set at 1,000N braking, when throttle = 0. (Vehicle will generate energy back into the batteries, first, and up to threshold. Beyond the threshold conventional friction braking is used.) The value of regenerative braking is particularly important to understand fully because it has been suggested that a high degree of regen-braking would make these vehicles less weight sensitive; heavier vehicles would recover their energy better or at least would not be penalized as much.

The current study is in part based off the previous Ricardo study (FB769) in that two of the previous vehicles, approximating the BMW Mini (small car) or the Saturn Vue (small SUV) where converted to an EV or PHEV. These baseline vehicles serve to provide the size, tire and aero losses. In the previous study, the powertrain was sized to perform with a "fully loaded" vehicle. In this study only the driver is considered. It should be noted that the current study did not consider the energy drain associated with power accessories, including brakes, steering or HVAC. The latter in particular can be quite significant since the AC can be 2-3 kW or larger.

It might be interesting to briefly contrast the power embodied in gasoline. One gallon of gasoline contains approximately 35 kWh of energy, before conversion with an ICE. So 16 kWh represents about 0.5-1.5 gallons of fuel depending on the assumptions for conversion to useable energy. We certainly need to be thinking about the equivalent of a 55+ mpg vehicle. (How these vehicles will be rated by the EPA is ongoing. Based on a proposed draft, the Volt has been rated at 230 mpg and 25 kWh per 100 miles.)

Mass of Vehicles and their associated Powertrains

In this study we consider a total of 16 vehicles or vehicle variants:

- Small car constructed in steel, or aluminum
- Small SUV constructed in steel or aluminum
- EV or PHEV
- 40 or 80 mile range

Since only the starting conventional (steel structure and ICE) curb masses are published, it is necessary to estimate the individual masses. (How much does the ICE weigh? What would the equivalent aluminum structure weigh?) Further, while the battery size and motor are directly calculated, this must be done in an iterative fashion because of a weight spiral up or down and its associated impact. (See slopes of response surface maps in Ricardo's Appendix.)

The mass breakdown for all vehicles is shown in the Appendix.

Vehicles are titled by their case number as follows:

- Case 1 = Steel PHEV
- Case 2 = Aluminum PHEV
- Case 3 = Steel EV
- Case 4 = Aluminum EV

And these are under the header of 40 or 80 mile range.

In this study since all vehicles are running only on batteries, the ICE in the PHEV is in effect a weight penalty that must be carried. There is an ongoing debate about the relative value/cost/performance of PEV vs. PHEV. PHEV certainly provide increased range and avoid the concern about running out of energy, but the cost and weight must be carried while performing as a PEV.

The Volt (PHEV) has a 53kW ICE-generator (1.4-liter, I4) to recharge the battery. It doesn't directly

drive the wheels, but it still requires a fuel system, exhaust, cooling etc. Since this ICE generator combo is quite unique with no published values, it was estimated at a 40 percent weight saving would occur, resulting in a 223 kg weight savings compared to a conventional small vehicle ICE powered vehicle. The SUV had a weight saving of 361 kg.

Results for Small Car

After several iterations for the various powertrain components, the results for the small car are summarized in Table 1. (Slide 21 in Ricardo report.)

Please note in Table 1 the battery cost gain (cost saving) relative to the Case 1 vehicle are given. (Case 1 is always the heaviest vehicle and hence has the largest battery pack. Case 4 is always the lightest.) While it is valid to compare all cases together, because in this study the vehicles perform the same task, it is probably more informative to compare Case1 vs. Case 2 and Case 3 vs. Case 4.) See later comments on cost.

Table 1.
Summary of Small Car results

Small Car Results



Small EV	Units	40 Mile Range				80 Mile Range			
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Vehicle Weight	kg	1284	1142	854	552	1284	1142	854	552
Exhaust Cost, Powertrain	\$	223	223	Fully Subtracted	Fully Subtracted	223	223	Fully Subtracted	Fully Subtracted
Base EV/ICE EV Weight	kg	1061	920	636	338	1061	920	636	338
Battery Size (kWh)	kWh	24.3	11.8	6.9	4.4	24.3	11.8	6.9	4.4
Range (km)	km	110	110	110	110	110	110	110	110
Battery Weight	kg	73	47	29	20	149	74	47	29
Motor + Controller Weight	kg	46	30	19	13	46	30	19	13
Powertrain Weight	kg	120	77	48	33	195	104	66	42
Weight Index 1	kg	1531	1037	704	465	1278	1153	853	585
Battery Size (kWh)	kWh	43.2	19.8	11.9	7.5	21.5	9.4	5.6	3.6
Range (km)	km	110	110	110	110	110	110	110	110
Battery Weight	kg	79	41	25	17	100	57	35	23
Motor + Controller Weight	kg	25	16	10	7	25	16	10	7
Powertrain Weight	kg	104	57	35	24	125	73	45	30
Weight Index 2	kg	1278	849	597	467	1202	1193	860	597
Un-optimized Battery Cost Gain	\$	\$0	\$822	\$2,077	\$2,769	\$0	\$1,211	\$4,164	\$5,654
Weight	kg	1272	1007	717	472	1272	1024	732	478
Weight Index	kg	1527	1,034	727	479	1,527	1,034	727	479
Weight Index	kg	1527	1,034	727	479	1,527	1,034	727	479
Weight Index	kg	1527	1,034	727	479	1,527	1,034	727	479
Battery Weight	kg	77	40	25	17	100	57	35	23
Motor + Controller Weight	kg	25	16	10	7	25	16	10	7
Powertrain Weight	kg	102	56	35	24	125	73	45	30
Battery Cost Gain	\$	\$0	\$1,938	\$4,933	\$6,706	\$0	\$1,211	\$4,164	\$5,654
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11
ICE/ICE Weight	kg	37	26	16	11	37	26	16	11

Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
 Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
 Case 3: Weight Represent a Full EV Configuration with Steel Structure
 Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

See Appendix A for plots

Energy Balance: Small Car

To understand better the summary in Table 1, it is informative to understand how the energy in the battery is expended. See slide 22 in Ricardo report. These percentage values are converted into an energy balance and are shown in Table 2.

Table 2.
Small Car Energy Balance as percent and absolute (kWh)

	Case 1	Case 2	Case 3	Case 4	Case 1 FTP kWh	Case 2	Case 3	Case 4
Aero	22.3	24.8	29.4	32.7	1.97	1.97	1.97	1.93
rolling	30.2	28.9	26.2	23.6	2.67	2.29	1.75	1.40
battery	4.1	4.1	4	3.8	0.36	0.33	0.27	0.22
converter motor/generator	7.6	7.5	7.2	6.8	0.67	0.59	0.48	0.40
differential	33.2	32.2	30.8	30.8	2.93	2.55	2.06	1.82
brake	2.5	2.4	2.3	2.2	0.22	0.19	0.15	0.13
regen	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01
FTP %	20.9	20	18.1	15.6	1.85	1.59	1.21	0.92

For the small car about 1.97 kWh (40 miles using FTP75) is required to overcome the aerodynamic losses, and this doesn't change as the vehicle weight changes. (Some small rounding errors occur across the different vehicles in the calculations.) As the vehicle gets lighter, the energy to overcome the rolling resistance decreases from about 2.67 to 1.4 kWh. For Case 1, more energy is required to overcome the rolling resistance, than the aero, but for the lightest vehicle, overcoming the aero losses is the largest energy drain.

During the drive cycle the regenerative braking returns about 1.85 kWh for the Case 1 vehicle, and about 0.92 kWh for the Case 4 vehicle. As a percentage of the rolling resistance they both recover about 65 percent. ($1.85/2.67=0.92/1.4$) The lighter vehicle is not disadvantaged.

Figure 1 depicts the Table 2 data graphically to better display the overall energy balance. (Negative values are for energy expended, positive from the regenerative gain.)

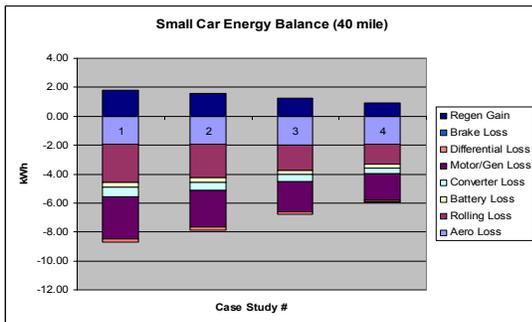


Figure 1. Illustrative Energy Balance for Small Car (40 mile range)

For FTP75 there are numerous stop/starts. The actual step by step regeneration is graphically presented in Figure 2. The difference between the yellow and white line represents the amount of energy recovered in the FTP75 drive cycle.

Small Car Brake Regen Example

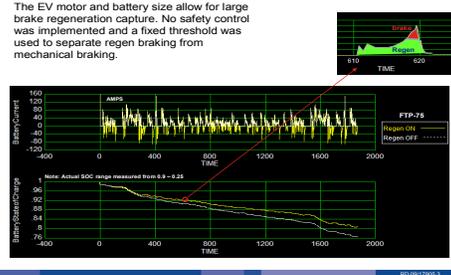


Figure 2. Regeneration Illustration

Please note the values in Figure 1 are for illustration purposes. The total individual values are correct, but positive contribution from the regenerative braking has already been factored into the overall sizing of the battery.

Small SUV

Table 3. Summary of Compact SUV results

Small SUV Results

	Small SUV EV	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Small SUV EV	2186	1987	1972	1972	1972	2025	2025	2025	2025
Base Weight	kg	1920	1850	1824	1792	1920	1850	1824	1792
Weighted Acceleration	kg	381	351	346	346	381	351	346	346
Base EV Range	mi	1307	1328	1314	1292	1307	1328	1314	1292
Energy Storage	kWh	117.7	117.3	117.3	117.3	117.7	117.3	117.3	117.3
Motor/Generator	kg	38	38	38	38	38	38	38	38
Converter	kg	45	45	45	45	45	45	45	45
Differential	kg	137	137	137	137	137	137	137	137
Battery	kg	1112	1108	1108	1108	1112	1108	1108	1108
Rolling Resistance	kg	112	112	112	112	112	112	112	112
Aero Loss (kWh)	kWh	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2
Rolling Loss	kWh	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
Motor/Gen Loss	kWh	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
Converter Loss	kWh	9	9	9	9	9	9	9	9
Battery Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Aero Loss	kWh	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Regen Gain	kWh	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
Brake Loss	kWh	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Differential Loss	kWh	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Motor/Gen Loss	kWh	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Converter Loss	kWh	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Battery Loss	kWh	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Rolling Loss	kWh	2.29							

Energy Balance Compact SUV

Table 4. Small SUV Energy Balance as percent and absolute kWh

	FTP %				Case 1 FTP kWh	Case 2	Case 3	Case 4
Aero	24.1	26.5	30.1	32.9	2.71	2.77	2.80	2.78
rolling	32.8	32.1	30.6	29	3.69	3.35	2.85	2.45
battery	4.1	3.9	3.6	3.3	0.46	0.41	0.33	0.28
converter	7.9	7.6	7.2	6.8	0.89	0.79	0.67	0.57
motor/generator	28.4	27.2	26	25.6	3.19	2.84	2.42	2.16
differential	2.7	2.6	2.4	2.2	0.30	0.27	0.22	0.19
brake	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01
regen	22.7	21.4	18.3	15.6	2.55	2.23	1.70	1.32

The energy balance for this vehicle is shown in Table 4.

More energy is expended to overcome the aero losses, but as a percentage they are quite close to the small car. The percentage of the energy and absolute amount to overcome the rolling resistance is higher than for the small car.

Influence of Range Requirements (40 vs. 80 mile range)

The calculations were repeated for an 80 mile range. (See Ricardo slides 21 and 24) Since the aero losses are somewhat similar, it is possible to look at the influence of range for both vehicles. Figure 3 plots the energy required (usable battery requirements) for both vehicles for both the 40 and 80 mile range.

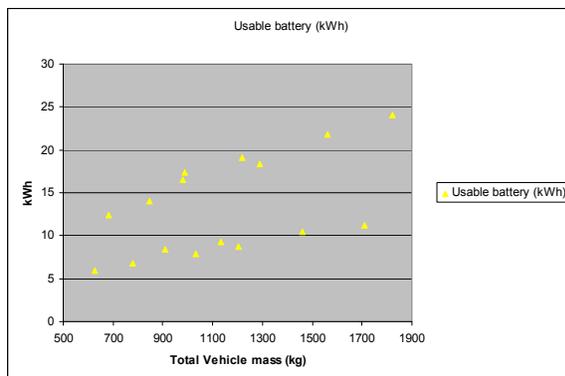


Figure 3. Energy Requirements, both vehicles. (80 mile range on top)

Comparison of the energy requirements indicates a small upwards weight spiral. For the heaviest vehicle, the battery increases 2.14 times to double the range. (The offset between the “paired” points for 40 or 80 miles is the additional incremental battery weight due to the weight spiral.)

Alternatively, the energy consumed per mile driven can be calculated and is shown in Figure 4. (Both vehicles)

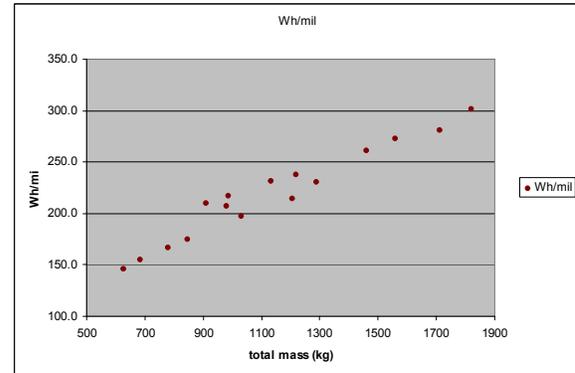


Figure 4. Energy Consumed per mile driven vs. total vehicle mass.

The energy requirements scale approximately linearly against vehicle mass. Consumption ranged from 0.146 kWh/mi for the lightest vehicle (627 kg) to 0.302 kWh/mi for the heaviest (1,822 kg). Contrasted to the specific battery output of 0.115kWh/kg results that the vehicle would require 1.5-3kg of battery for every mile traveled.

Cost

A detailed cost analysis has not been done. Many of the component costs are evolving or only approximate cost data is publicly available. But a few comments can be made. The total battery requirements ranged 9.1 to 36.9 kWh. At \$750/kWh this represents a cost of approximately \$7,000 to \$28,000.

More interesting is to compare the incremental battery size between Case 1 and 2, and Case 3 and 4. In this case the incremental battery size grows from approximately 1.2 to 3.4 kWh. And the motor requirements grow up to 15 percent with the associated increase in controller costs to handle the high loads. Certainly the aluminum structure has an incremental cost increase, but all in, the lightweight structures should be less expensive in the range of \$1,000 to \$3,000.

Alternatively the lighter structures could be used to extend the range of the vehicles. The slope of the response map in the Ricardo Appendix indicates that for large mass saving, where the weight spiral becomes significant, the range can be extended approximately equal to the mass saved. For the vehicles studied, a 20 percent weight reduction (PEV) produced a range increase of 14 percent.

SUMMARY

Sixteen vehicles (small car, small SUV, EV, PHEV (running as EV), aluminum structure, steel structure, 40 or 80 mile range) were modeled using FTP75 drive cycle with an energy consumption ranging from 0.146 kWh/mi to 0.302 kWh/mi. Contrasted to the specific battery output of 0.115 kWh/kg results that the vehicle would require 1.5-3 kg of battery for every mile traveled.

The associated battery energy (rated/useable) ranged from 9.1/5.92 kWh to 36.9/24 kWh.

The associated vehicle mass ranged from 627 kg to 1822 kg. No additional mass was added to “support” the battery. Battery mass ranged from 51 to 209 kg. (For the lighter vehicles, the battery weight is approximately equal to the weight of a tank of gas.) Contrasted against the 16 kWh, 170 kg Volt battery suggests this study has calculated the battery energy requirements quite well, but might have underestimated the overall battery mass. However the effect of vehicle mass vs. battery requirements does appear to have been well captured

The battery size (kWh) requirements scaled approximately linearly with range, though as the vehicles got heavier, a small weight spiral became more noticeable. Similarly, as the range is increased beyond 80 miles, this weight spiral would be expected to be more pronounced.

Regenerative braking was applied to all vehicles. For the FTP75 drive cycle, about 65-69 percent of the rolling resistance energy could be recovered, irrespective of the vehicle mass. This equates to 15.6-23 percent of the total energy. (As the vehicle gets lighter the percentage of energy allocated to “aero” grows relative to the rolling resistance. For the HWFET the regenerative recovery drops to 2.8-5.3 percent of the total energy.)

The range of the vehicle is dominated by the sizing of the battery. The next largest factor is the vehicle mass, since about 30 percent of the energy is used to overcome the rolling resistance in the FTP75 cycle.

Vehicle mass reduction can reduce the battery size requirements by about 10 percent, or about 1.2 to 3.4 kWh, for the vehicles studied.

With such a relatively small amount of energy contained in the batteries, all aspects of the vehicle must be carefully optimized to produce a vehicle of acceptable range, performance, and cost. Battery cost dominates. Reducing the vehicle mass to reduce the battery capacity requirements appears to be cost effective and should be further quantified with an LCA type analysis. Tesla Motors, Fisker Automotive and Bright Automotive are all using lightweight aluminum to reduce the mass of their vehicles.

Other OEM’s have opted for a more or less tradition body structure, with some light weight components for their first generation vehicles while their efforts are directed to developing a robust propulsion system. The current study suggests that mass reduction and improved aerodynamics will be a high priority for a sustainable, affordable vehicle.

Appendices

The starting point for the vehicle mass breakdown comes from the first and second IBIS studies based on the mid-sized Ford P2000 architecture. The actual weights for the vehicle structure and closure panels in steel or aluminum are known. The powertrain and other masses for glass, interior, etc. could be estimated from IBIS regression analysis. The “steel” vehicle mass breakdown for the mid-sized, 1,533kg, vehicle is shown in Figure A1. The corresponding “aluminum” vehicle at 1,270 kg is shown in Figure A2.

The powertrain accounts for about 45 percent of the overall mass. The steel BIW is about 18 percent, the closures about 5 percent of the overall vehicle mass. While more mass is certainly saved with the aluminum structure, slightly different percentages arise, since not all components can be resized. (The glass and interiors remain unchanged and grow in percentage terms.)

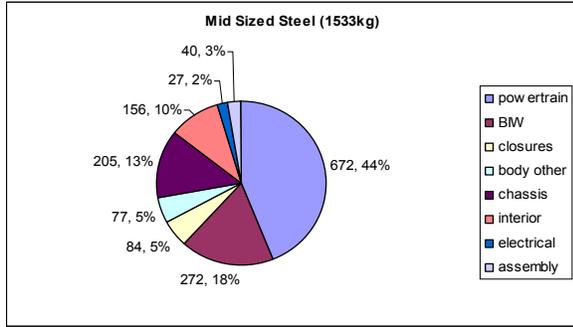


Figure A1. Mid-Sized “Steel” Vehicle with Conventional ICE by kg and percent.

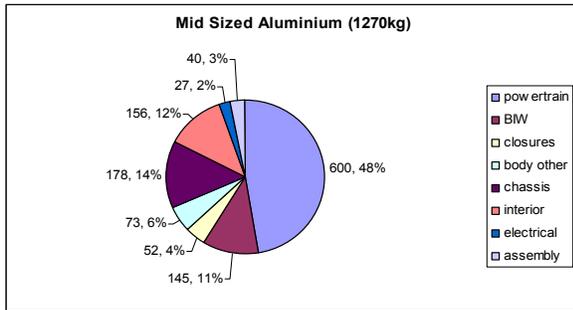


Figure A2. Mid-Sized “Aluminum” Vehicle with Conventional ICE by kg and percent.

It should be noted the mass of the powertrain includes all fluid masses, as well as exhaust, cooling, starter battery and engine cradle etc.

For this PEV study, the curb masses of the conventional small car and small SUV are reported as 1,304 kg (2,874 lbs) and 1,928 kg (4,249 lbs) respectively. To estimate the BIW mass in either steel or aluminum, a regression technique based on the vehicle size is used. (Warren 1997) The weight savings of the closure panels can be directly calculated, and the other masses estimated from regression analysis.

Small Car

The resulting mass breakdown for the small car PEV in steel, after the battery mass and motor have been calculated, is shown in Figure A3. See Ricardo report for full details on calculations for batteries, motor etc.

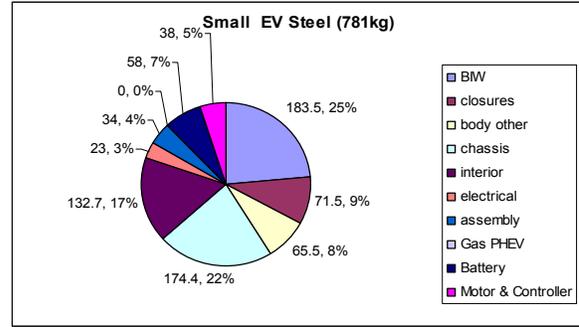


Figure A3. Small car “Steel” EV for 40 mile range.

The corresponding vehicle in aluminum is presented in Figure A4.

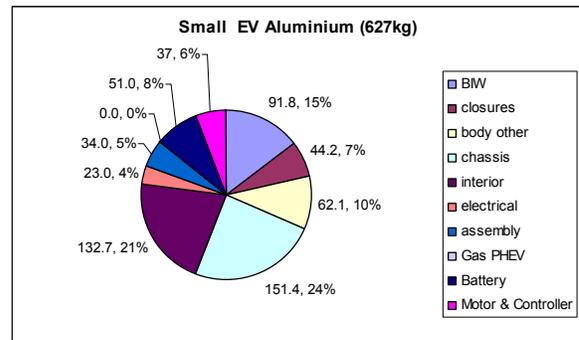


Figure A4. Small car “Aluminum” EV for 40 mile range.

The mass of the aluminum BIW is reduced to only 92 kg. As a reference point the BIW for the Audi A2 aluminum structure was 110 kg, and this was a larger vehicle.

PHEVs (Small Car)

Figure A5 is for the “steel” PHEV. Figure A6 is for the “aluminum” PHEV.

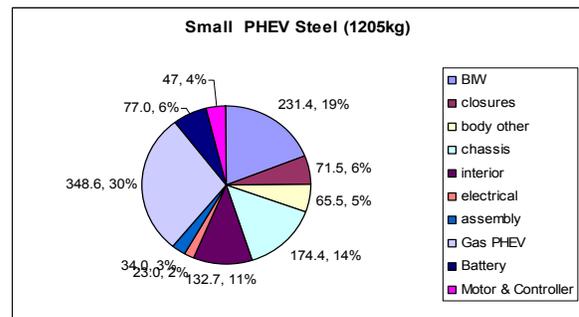


Figure A5. Small car “Steel” PHEV for 40 mile range. Case 1.

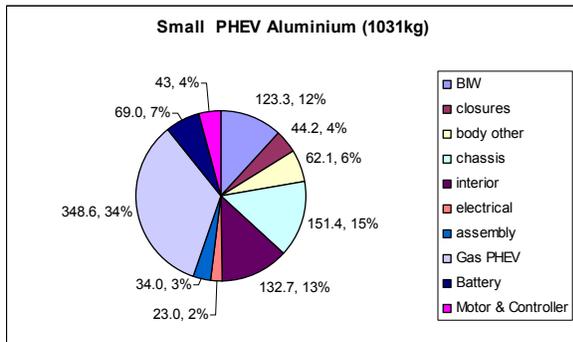


Figure A6. Small car “Aluminum” PHEV for 40 mile range.