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Viewpoint

Batteries: Lower cost than gasoline?

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ABSTRACT

We compare the lifecycle costs of an electric car to a similar gasoline-powered vehicle under different scenarios of required driving range and cost of gasoline. An electric car is cost competitive for a significant portion of the scenarios: for cars of lower range and for higher gasoline prices. Electric cars with ~150 km range are a technologically viable, cost competitive, high performance, high efficiency alternative that can presently suit the vast majority of consumers' needs.

1. Introduction

The well-to-wheel efficiency of battery electric vehicles (BEVs) is on average 2.6 times greater than that of similar performance internal combustion engine (ICE) vehicles (Unnasch and Browning, 2000), and BEVs represent carbon-free transportation when electricity is generated renewably. BEVs also require significantly less maintenance and repair than ICE vehicles due to having only one moving part in the electric motor. For these reasons, BEVs are an ideal energy-efficient replacement for ICE vehicles. However, BEVs are often ruled out due to high capital cost (Borenstein, 2008). This cost grows linearly with the size of the battery pack, or the maximum range of the car. Still, this cost premium for BEVs is compensated by the low cost of electricity compared to gasoline. Our objective is to show which factors affect the cost of driving, for consumers and policy makers to use as we rethink transportation.

In 1996 General Motors introduced the first generation EV1, which ran on lead–acid batteries and had a range of 90–120 km on a full charge. The second generation EV1 used newer nickel–metal hydride batteries and could achieve a range of about 135 km. The development of lithium-ion battery technology allows for greater range, reduced weight, and approximately double the lifespan of nickel–metal hydride batteries. The more recent development of nanotechnology-based lithium batteries allows for even greater lifetime and the ability to fully charge a battery pack in under 10 min (Altairnano, 2008).

A major component of electric vehicle cost is for batteries. Lithium-ion batteries have decreased greatly in price over the last 10 years and this trend is expected to continue (Anderman, 2004). As the technology has developed, weight has also decreased (Broussely, 2004). The development of nanotechnology-based lithium-ion batteries has allowed for much faster charging and discharging along with greater lifespan, potentially up to 15,000 deep discharge cycles (Altairnano, 2008).

2. Methodology

To effectively determine the lifecycle cost we analyzed electric and ICE vehicles that are very similar: two sports cars and two economy cars. The *gasoline* Lotus Elise sports car and the *electric* Tesla Roadster are similar in dimensions and performance and are built on near-identical frames. The *gasoline* Scion xb is compared to the *electric* AC Propulsion E-box. AC Propulsion produces the E-box from a Scion xb by replacing the gasoline drive train with an electric drive train. Data for the vehicles and the calculations are contained in the supplemental material (available on the web), and are summarized in Figs. 1 and 2.

Increasing the range of the car profoundly increases the cost of the BEV because of the increased battery pack and associated costs, where enlarging the gas tank of the ICE presents no added cost. Therefore, the BEV is more cost effective than the ICE when a shorter driving range is required. The "equal cost electric range" is where the lifecycle costs of the ICE and BEV are equal, and below which the BEV has a smaller lifetime cost. For example, increasing the cost of gasoline increases the equal cost electric range as does decreasing the cost of batteries.

The cost of ICE vehicles is broken down into three categories: purchase price, maintenance, and gasoline. Maintenance only includes regularly scheduled maintenance, but not repairs. The BEV cost is broken into four categories: purchase price without batteries, maintenance, electricity, and batteries as function of desired range.

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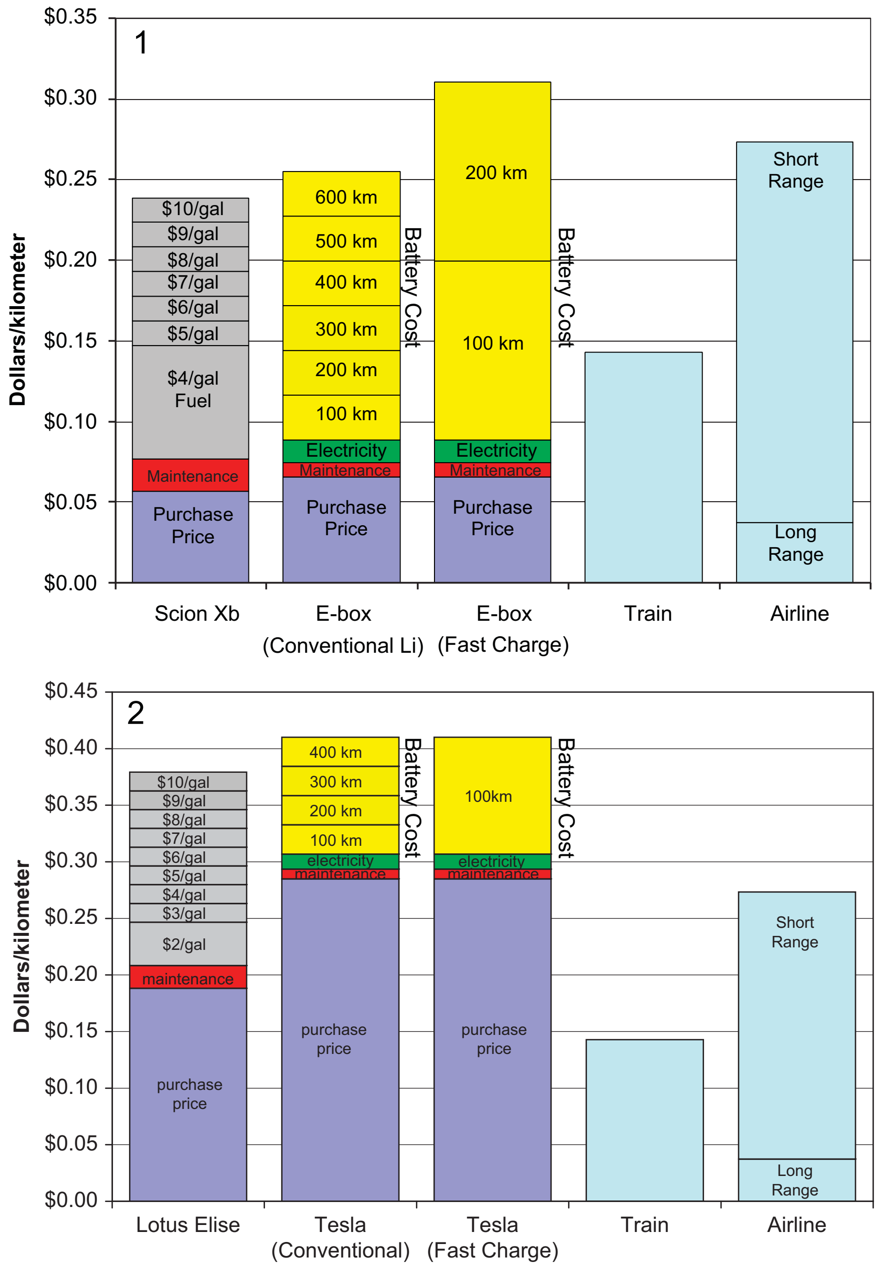

Figs. 1 and 2. Show total lifetime cost of three vehicles in dollars per km. These are compared to averages for airline and train travel. The gasoline prices shown are the average price of gasoline over the 12-year lifespan of the car. The purchase price for the electric cars is the price of everything except the battery pack. Battery cost is given in terms of range (km).

The E-box is not manufactured initially as an electric car, but is converted from the ICE Scion xb, at about one per month. The costs are adjusted accordingly: we subtract the cost of labor from the conversion, and are left with $10,000 due to the cost of the electric motor and related components. Additionally, we subtract the cost of the gasoline components that are removed ($7400).

We included 13 maintenance items for ICE vehicles, and 5 maintenance items for electric vehicles (see supplemental online materials). We assumed that brake pads and rotors would have double the lifetime of those on the gasoline vehicles due to regenerative braking. While the initial investment of an electric car is higher, the electric car will require less money each year. Future savings were discounted to present values (PV), accordingly:

$$PV = \frac{C}{(1+D)^Y} \tag{1}$$

PV is present value, *C* is cost, *D* is discount rate (we used 7%), and *Y* is the number of years since the initial purchase. Then the present value costs for each year are summed over the 12-year lifetime to give the lifetime cost. We choose a 12-year lifetime, consistent with the other studies (Greene and DeCicco, 2000).

We chose a discount rate of 7% as it is an average rate of return for investments and thus reasonably represents the opportunity cost of the purchase. There is disagreement on what should be the appropriate discount rate. A recent study determined that consumers generally would not invest in economy technologies unless the financial payback time is very short (Greene and DeCicco, 2000). Thus, buying behavior is consistent with rational behavior under a very high discount rate (~16%). Because we are comparing the *actual* lifetime costs that a vehicle owner incurs, rather than the *perception* the owner has on what is cost effective, 7% is the appropriate discount rate. A sensitivity analysis indicates that the discount rate significantly affects the result. Increasing the discount rate from 7% to 16% decreases the equal cost electric range by 41%.

To determine gasoline costs, we assumed that prices would increase linearly with time. The average price of gasoline in each year was multiplied by the number of gallons consumed. This was converted to present value (Eq. (1)), and the cost for each year was summed to give the total cost of gasoline. This was repeated for each different average gasoline price. The price shown for gasoline in Figs. 1 and 2 is the average price of gasoline over the 12-year lifespan of the vehicle. We used the United States national average price of electricity of 10.4 ¢/kWh, and assumed it would increase with inflation as this has been the trend for the past 10 years (EIA, 2007). The present value and lifetime electricity cost were calculated consistent with the method for lifetime gasoline cost.

Nighttime charging rates may be considerably less than 10.4 ¢/kWh in some areas. The electricity cost is small, so the results are not sensitive to it, a 50% increase in the cost of electricity resulting in a 10% decrease in the equal cost electric range. The inflation-adjusted price of electricity in the United States has stayed fairly constant, over the last 10 years (EIA, 2007). Although petroleum, natural gas, coal, and uranium will likely increase in price, wind and solar power are projected to decrease in price and be able to provide relatively cheap and clean electricity to power the new fleet of electric cars. It is likely that gasoline prices will continue to increase, because unlike previous gasoline cost increases, the present escalation is due to diminishing production and increasing demand. With battery prices declining and gasoline prices increasing, the economic advantage will continue to shift in favor of electric travel.

3. Results

There is a significant range of scenarios under which use of BEVs is cheaper than ICE vehicles. For a battery cost of $500/kWh, our model yields an equal cost electric range for the economy cars of 139 km if the price of gasoline remains constant at $3/gal for the next 12 years. However the equal cost electric range increases to 331 km if gasoline increases in cost to $10/gal over the next 12 years. Mass production will result in decreased cost of both the electric motors and batteries. The comparison in capital costs for the Elise and Tesla cannot represent future market prices, because the Tesla is still an experimental car, where there have been 12,000 Elises produced, over 50,000 Lotuses produced, and a billion ICE vehicles produced. The comparison of the economy cars (Fig. 1) may be more correct, because only the electric motor system is priced, although the treatment of labor costs represents a significant uncertainty, because subtracting the cost of labor and the cost of (removed) ICE components from the electrical conversion cost was used to calculate the cost of electric vehicle components. For instance, if the cost of electric vehicle components (economy car) were in fact $5000 (or 18% greater than that calculated), the equal cost electric range (at $5.00/gal gasoline) drops by 25%. Very few high-performance AC electric motors have been produced for automobiles, and it is reasonable to presume that with mass production the smaller, lighter electric motor with a single moving part will be less expensive than the corresponding ICE.

4. Convenience

The ability to drive long distances in a single sitting has come to be assumed as part of owning a car. However, the expense, environmental impact, and political consequences of gasoline consumption compel us to consider negotiating this ability. Because 78% of Americans drive 40 miles (64 km) or less each day (Fig. 3) (DOT, 2003), the majority of our transportation needs can be met with shorter-range electric automobiles. Should someone need to drive farther than their battery capacity allows, there are several solutions including: quick charge technology, public transit, and ICE/hybrid vehicles for rent, or that may exist in some families as a second car. The loss of range is an inconvenience, but should be weighed against the present inconveniences assumed by the owner of an ICE vehicle:

(1) Inability to refuel at home, requiring stops at a gas station. A BEV can "refuel" at most places it can park.
(2) Increased maintenance trips such as changing of engine fluids.
(3) Increased repairs due to greater complexity of the ICE.

In time, the financial, environmental, and political costs of owing an ICE vehicle may grow. Independently, accommodations

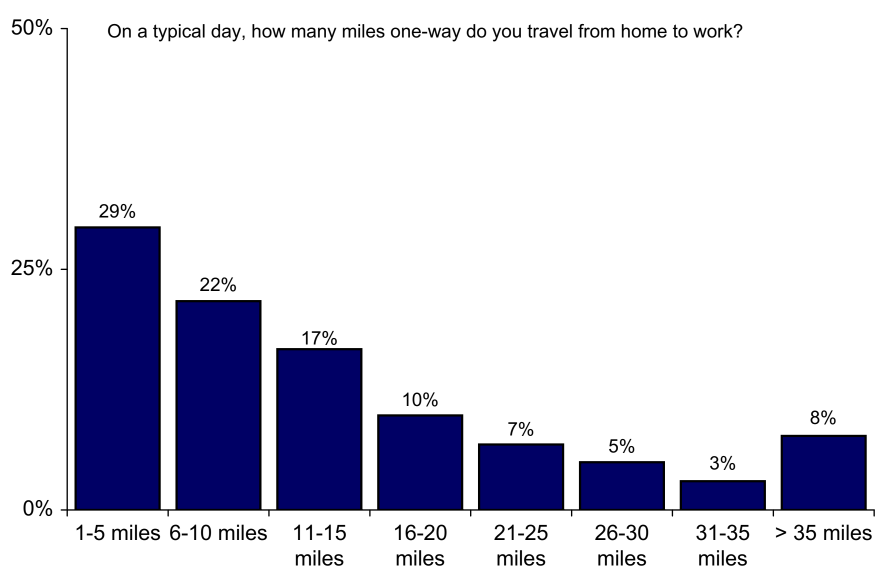

Fig. 3. Omnibus household survey. Aggregated data cover activities for the month prior to the survey. *Source*: US Department of Transportation, Bureau of Transportation Statistics. Volume 3, Issue 4 October 2003.

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for electric travel may improve such as improved charging infrastructure. Lastly, while electric technology is presently competitive with ICE transportation, technology improvements will increasingly favor the BEV. All three of the above progressions will push the scales in favor of electric travel.

5. Power density qualification

Very short-range electric vehicles are not possible because of presently limited Li-ion battery *power density* of about 1 kW/kg (see supplemental online materials for accompanying paper: Fischer et al., 2009). The power requirements for the Tesla require a 200 kg battery, or a minimum range of 125 km. Additionally, in a low state of charge, the battery experiences enhanced degradation under maximum power load, which can be prevented by reducing delivered engine power when the battery is in a low state of charge. Both the Tesla and E-box have extremely high acceleration. Lower power electric vehicles, corresponding to present economy cars, will be able to have smaller battery packs, range, mass, and cost.

6. Conclusion

Because the vast majority of American travel consists of short trips as is shown in Fig. 3 (92% of trips are 35 miles or less), the use of a shorter-range, full performance electrical vehicle where appropriate can result in considerable decrease in transportation costs. Electric vehicles have the potential of being less expensive while reducing both emissions (including greenhouse gasses) as well as dependence on oil purchased from potentially unfriendly political regimes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2009.02.045.

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