Determining the Cost Effectiveness, Emissions Reduction, and Power Consumption of Full Scale Adoption of the Electric Vehicle

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Abstract

The electric vehicle as a viable mode of mass transportation has not been previously investigated. This investigation combines the cost effectiveness, emissions of green house gasses, and national power generating capacity, of large scale adoption of the electric vehicle. Total miles driven by electric vehicles were plotted as a percentage of total miles driven in the United States annually to find the effects from 0% to 100% adoption. It was found that while the electric vehicle significantly reduces CO$_2$ emissions it does so at a higher cost per mile to the consumer. Our national power generating capacity was found to be a limiting factor to full scale adoption of the electric vehicle. In the case of 100% adoption the residential sector as a percentage of total annual energy consumption in the U.S. grew 41.6% and total consumption grew by 10%.
1 Introduction

1.1 Goals

The goal of this investigation is to determine how much we would need to increase generating capacity to provide power to full scale implementation of electric vehicles. A supplementary goal of this investigation is to determine the rate at which electric vehicles reduce greenhouse gas emissions and the consumer cost of achieving this reduction.

1.2 Greenhouse Gas Emissions

Concerns over rising levels of greenhouse gas emissions has strengthened the green revolution. Fossil Fuels are carbon based and are the largest contributor of CO\textsubscript{2} with 80\% of all greenhouse gas emissions\cite{1}. Therefore in hopes of reducing emissions, demand is shifting to ecofriendly technologies. The increase in demand for safe, practical, and rapid energy transfer has pushed traditional wire based transfer to its limits. However with the advances in wireless power transfer many of these limits can be exceeded. Increased efficiency in Inductive Power Transfer (IPT) shows promise in solving the problems of traditional methods, specifically in the realm of charging devices such as electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs).

Carbon footprint is a represents the total carbon dioxide emissions due to a specific person or object in a given amount of time. Carbon footprint is directly proportional to the thermodynamic efficiencies of the object in question. For electric vehicles it is largely determined by the efficiency of the electric motor and the charging efficiency of the batteries. For gas powered vehicles it is the fuel efficiency of the engine. Efficiency in general is the key to reduction in greenhouse emissions. It reduces the load on power production, consumption of natural resources, and promotes growth in renewable energy infrastructure.
1.3 Sources of Electricity Generation

The four main sources of electricity generation in the United States are coal, natural gas, nuclear, and hydroelectric conventional. They combine to produce more than 95% of the electricity consumed in the United States. [2] Figure 1 shows the distribution in detail. Of the four main sources of electricity generation coal power is the greatest contributor to carbon dioxide emissions. Coal emits between .8 and 1 kilogram of carbon dioxide per kWh generated. Natural Gas follows coal in emissions with between .4 kg and .6 kg of carbon dioxide emitted per kWh of energy generated. [3] Nuclear and Hydroelectric generation yields negligible amounts of carbon dioxide emissions.

![Figure 1: U.S. energy production by source](image)

1.4 Electric Vehicle Market Research

The electric vehicle industry is growing at a rate greater than that of the availability of charging stations and personal charging technologies. This is a limiting factor in the range and practicality of EVs. However, even without the promise of adequate charging technologies
the percentage of EV and Hybrid Electric Vehicle (HEV) sales versus all other automobiles have grown from .06% in 2000 to 2.01% in 2011 [4]. Prior to the recession in 2009 this percentage peaked at 2.79%. [4] Growth projections for HEV and EV sales are showing a 5%-30% share of the market by 2025.[5] This demonstrates a need for a growth in the charging industry.

2 Electric Vehicles Versus Gas Powered Vehicles

2.1 Electric Motors

EVs are powered by electric motors. An electric motor works by using the principle of induction and the magnetic forces associated with it. Motors have loops of wire in a magnetic field, when current is passed through these loops a magnetic force is exerted on them creating a torque and rotating a shaft. Electrical energy is converted into mechanical energy in this process. The equation for torque $\tau$ is given by:

$$\tau = NIAB \sin \phi.$$ 

Where $N$ is the number of turns, $I$ is the current, $A$ is the area of the loop, $B$ is the magnetic field, and $\phi$ is the angle between force and pivot arm.
2.2 Internal Combustion Engines (ICE)

An ICE is powered by the combustion of a fossil fuel with an oxidizer (normally air) in a combustion chamber. In the combustion process high temperature and high pressure gases are a byproduct. The expansion of these gases apply a direct force on a piston. The force moves the piston linearly over a distance which is then transformed to rotational motion and moves down a series of components to finally power the turning of the wheels. This process transforms chemical energy into useful mechanical energy.

2.3 Heat Generation

The heat generation of electric motors is mostly attributed to resistance in the electric transmission wires, however this heat is relatively negligible. Internal Combustion Engines produce a large amount of heat from the process of transforming chemical energy to mechanical energy. This heat is dispersed by the radiator which is either air cooled or water cooled. This heat is responsible for most of the energy loss in the ICE system, energy loss when powering a vehicle is a source of inefficiency. However, in cold climates the heat generation due to an ICE is an advantage, it can be transferred into the cabin of the car to warm the passengers. In an electric vehicle this heat generation must come from electrical resistance thus depleting the batteries at a greater rate and limiting the range of the vehicle.

2.4 Components

Electric motors intrinsically have less parts, dynamic and static, than an ICE. This gives the electric vehicle an advantage in the cost of maintenance, less parts means less opportunity for a part to fail. Some of the main parts on an ICE that are not present in an electric motor are the pistons, piston casings, fuel injector, and radiator. Therefore electric vehicles
normally are lighter than their gas powered cousins. A measure of the overall performance of any drive train is the power-to-weight ratio. Less components allows electric vehicles to have a lower energy input when holding power-to-weight ratio constant.

2.5 Power Transportation

Regardless of whether chemical or electrical energy is used to power a vehicle, the way in which the energy arrives at the final place of consumption must be considered. Electrical energy is transported via power lines which span the entire country. One of the limitations of power lines is that they have high resistive loses when transporting electrical energy over great distances. To understand power loss we must examine two equations:

\[ Power = I \times \Delta V \]  
\[ PowerLoss = I^2 \times R \]

Where R is resistance, \( \Delta V \) is voltage difference, and I is current.

To reduce power loss the direct proportionality of I and V in equation (1) are exploited. Holding power constant, voltage is stepped up to extremely high levels thus causing current to become small. With a small current, the effect of resistance on power loss in equation (2) is greatly reduced due to the \( I^2 \) term.
3 Methods of Research

3.1 Research Model

Following Fermi’s estimation technique the benefits from large scale adoption of the electric vehicle was determined. Two highly efficient gas powered models, the 2012 Toyota Camry SE and the 2012 Honda Civic Sedan, were chosen based on consumer interest and similarity to model type of the Nissan Leaf. Each vehicle was compared independently to the Nissan Leaf. The study compared the vehicles from a 0% to 100% adoption rate based on three elements, cost effectiveness, carbon dioxide emissions, and electricity consumption.

3.1.1 Cost Effectiveness

For the Camry and the Civic the cost effectiveness was calculated by first finding the cost per mile driven as a function of the vehicle’s city miles per gallon, 25 and 28 respectively, at four dollars per gallon of gas. Cost per mile due to depreciation was found by dividing total cost, $23,000 MSRP for the Camry and $15,955 MSRP for the Civic, of the vehicle by the estimated 150,000 mile life of the engine. Maintenance cost estimates were also generated. The sum of the values was determined to be the total cost per mile for the gas powered vehicles. In a similar fashion the cost effectiveness of the Nissan Leaf was calculated using the 2010 residential cost per kWh and dividing it by the miles per kWh as stated by the manufacturer. This was then added to the cost per mile due to depreciation found through dividing the $35,200 MSRP of the Nissan Leaf by the estimated battery pack life of 150,000 miles. The manufacturer warranties the Nissan Leaf battery pack to 100,000 miles which can be assumed to be on the lower end of the life expectancy.
3.1.2 Carbon Dioxide Emissions

Before the emissions per mile of each vehicle were able to be calculated the amount of carbon dioxide emitted from each type of energy generation method was needed. The emissions from each fuel source is as follows: gasoline yields 8.9 kilograms of carbon dioxide per gallon, Coal yields .8 to 1 kg of CO$_2$ per kWh generated, natural gas yields .4 to .6 kg of CO$_2$ per kWh generated, nuclear and hydroelectric generation of power yields negligible levels of CO$_2$. The averages of each range were chosen for simplicity. For the Nissan Leaf consideration to the source of electricity was given. In 2011 43% of electricity was generated by coal, 25% was generated by natural gas, 19% was generated by nuclear power plants, and 8% was generated through hydroelectric power plants. [2]

The CO$_2$ emissions calculation for the gas powered vehicles was done by dividing 8.9 kg of CO$_2$ per gallon by the respective miles per gallon for each vehicle. According to the previously outlined sources of electrical generation, the Nissan Leaf yields .55 kg of CO$_2$ per kWh consumed. Dividing this number by the 3.125 miles per kWh gave the total kg of CO$_2$ emitted per mile driven. Once these values were determined for each vehicle an equation was built to plot the reduction in CO$_2$ emissions as a function of total miles driven in the United States by electric vehicles.

Once values for each vehicles emission per mile were found an equation was generated to plot the emissions as a function of total miles driven by electric vehicles. This equation attempts to explain the change in emissions if any percentage of annual miles driven by gas powered vehicles in the United States were instead driven by electric vehicles. The emissions growth due to kWh consumption for the Nissan Leaf:

$$y_{\text{leaf}} = 0.1776x$$  \hspace{1cm} (3)
Combining this equation with the emissions reduction due to the transition away from gas powered vehicles yields the emissions equation for the Toyota Camry:

\[ y_{\text{camry}} = 0.1776x + 0.356(100 - x) \]  

(4)

The emissions equation for the Honda Civic:

\[ y_{\text{civic}} = 0.1776x + 0.317(100 - x) \]  

(5)

### 3.1.3 National Power Production Capacity

Our capacity to generate power in the United States was predicted to be a limiting factor in the adoption of electric vehicles. To determine the validity of this prediction the current power production capacity of the U.S. was found. For the calculations done in this study it was assumed that all power plants would operate 24 hours a day 365 days a year at full capacity. In reality this is not the case but this study focuses on the extremes of full scale adoption of electric vehicles where, logically, power production will increase. Therefore, the assumption is acceptable in this context. Once this assumption was made the calculation became simply multiplying the production capacity by the hours in a year to find the maximum kilowatt hours that could be produced annually. This was then compared to the current consumption in the residential, industrial, commercial and transportation sectors to find the amount of kilowatt hours available for consumption. Finally the increase in kilowatt hours consumed (accounting for resistive losses) when electric vehicles accounted for 100% of miles driven in the U.S. annually was added to the equation to determine whether it was in fact possible for our power grid to support.
4 Results

4.1 Cost Effectiveness

From Table 1 we can draw that the Nissan Leaf is cost competitive at 4$ per gallon of gas. It has a lower cost per mile than the Camry but a slightly higher cost per mile than the Civic. This indicates that the Nissan Leaf’s claim to save money based on high gas prices is dependent on what gas powered model the cost is compared to at 4$ per gallon. It costs almost 5 cents more per mile than the Honda Civic which is of similar size and model type. It is about 4 cents cheaper per mile than a Toyota Camry, a slightly larger model. However, in Table 1 implies that if we compare increasing gas prices it becomes clear that the Nissan Leaf is more cost effective than gas powered models.

Table 1: Cost per Mile Driven (U.S. Dollars)

<table>
<thead>
<tr>
<th>Price of Gas ($/gal)</th>
<th>Nissan Leaf</th>
<th>Toyota Camry SE</th>
<th>Honda Civic</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>.271</td>
<td>.313</td>
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<td>5</td>
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<tr>
<td>8</td>
<td>.271</td>
<td>.473</td>
<td>.392</td>
</tr>
</tbody>
</table>
4.2 Emissions

Figure 2 indicates that as we move towards full scale adoption of electric vehicles, CO$_2$ emissions will be reduced. If 100% of the miles traveled in America were done so by the Nissan Leaf instead of the Toyota Camry, $5.3520 \times 10^{11}$ kg less of CO$_2$ would be emitted annually, a reduction of 51.2%. In the 100% case for a Honda Civic a 44% reduction in CO$_2$ emissions equaling $0.4182$ trillion kg was calculated. If only 25% of miles were driven by a Nissan Leaf instead of a Toyota Camry, $0.1338$ trillion kg less of CO$_2$ would be emitted, a reduction of 12.5%.

These findings confirm the claim that electric vehicles will in fact reduce greenhouse gas emissions. The EIA estimates that U.S. gasoline and diesel fuel consumption for transportation in 2011 resulted in total emissions of $1.519$ trillion kg of CO$_2$. When the 100% electric scenario was plotted against current annual CO$_2$ emissions there was a reduction of $0.986$ trillion kg of CO$_2$, this is a reduction of 65%. When combined with the findings of cost per mile it is clear that on the micro level one does not need to sacrifice monetary means to reduce CO$_2$ emissions. This is a good sign for environmentalists because low consumer costs will be a driving factor in consumer demand for adoption of the electric vehicle on a macro level.
Figure 2: Kilograms of CO$_2$ emissions as a function of total miles driven by electric vehicles in the United States. The dark green line is a 2012 Toyota Camry SE and the light blue line is a 2012 Honda Civic.
4.3 Transportation Sector

Examination of Figure 3 reveals that energy consumption in the transportation sector will grow due to the transition to electric vehicles. The increase in energy consumption will simultaneously reduce the transportation sector's dependence on petroleum. Because the transportation sector currently has a 99% reliance on petroleum-based energy, there will be a gap in chemical energy source and total energy consumption, this gap will then be filled by electrical energy consumption. Electrical energy will need to be somehow routed into the transportation sector, as there is no current infrastructure to accomplish this feat. Therefore, electrical energy may be routed through the other sectors, the implications of which are discussed in the next section.

Figure 3: Energy flow in the United States in 2009 in units of QBtu, created to give a visual representation of useful versus lost energy. Generation is arranged by source. Consumption is arranged by sector. (Source: Lawrence Livermore National Laboratory (2009))
4.4 National Power Production

According to the EIA the United States of America currently has the capacity to produce 21.99 trillion kWh annually.[6] The current annual consumption for all sectors was found to be 28.72 trillion kWh, it should be noted that the residential sector accounts for 22% of this number.[6] This discrepancy between production and consumption is overcome due to energy imports from other countries. This also implies that we are already operating at our full production capabilities. Under the 100% electric vehicle scenario, annual consumption grew by 2.88 trillion kWh this is a 10% increase in total energy consumption. Furthermore the residential sector's share of total energy consumption grew 41.6%, this is displayed visually in Figure 4. When converted back to power it was determined that in the 100% electric vehicle scenario approximately 232 more nuclear power plants or 20,800 more wind turbine farms would be required to support this increase in consumption. As a frame of reference there are currently only 66 operating nuclear power plants and 689 wind turbine farms in the United States. This indicates that our current power generation capacity could not sustain full scale implementation of electric vehicles and charging stations.
Figure 4: Growth in residential sector electricity consumption as a function of total miles driven by electric vehicles in the United States this is displayed as the middle blue line. The light cyan line is current annual consumption, the dark red lines are 5% error bars.
5 Further Research

Using physics, we can solve the mystery of the effects of transitioning to electric vehicle use. This gives us a direction to move towards in hopes of reducing greenhouse gas emissions. However there are vested political and economic forces at work which will cause the transition to electric vehicles to be extremely slow.

5.1 CO$_2$ Emissions in Other Sectors

Although it is clear that adoption of the electric vehicle will reduce CO$_2$ emissions in the transportation sector, it is unclear whether this would be offset in some other sector. While we can confidently say that initially demand for gasoline and in effect oil would fall due to less gas powered vehicles, this cause oil prices to plummet. Therefore, consumers may move to oil dependence in other sectors. How much would this offset the reduction in emissions in the transportation sector?

5.2 Second Order Effects

In the presence of a large electric vehicle fleet, the increase in gas powered miles driven due to lower gas prices and cheaper costs per mile is a second order effect that would be difficult to measure experimentally. However, one could theorize about this effect and given more time may be able to come up with a more complex equation for CO$_2$ emissions.

Electricity prices are determined like any other consumer good, by supply and demand. Demand at night time is lower and therefore the cost of electricity is lower. However, consumers would likely charge electric vehicles during the late night hours because they are in use during the day and with a long recharge time this would be the perfect time to charge.
Therefore, in the presence of a large electric vehicle fleet the demand in the evening would be higher and thus cost of electricity would also increase. The effect that increased demand at specific times of the day on the cost per mile for the Nissan Leaf is immeasurable. Again this is a second order effect.

5.3 Projected Growth

Building a regression model for the growth of electric vehicle sales would give a more accurate depiction of the rate at which electric vehicles are being assimilated. This model would be based on a time series panel data set with annual sales per state as unit of observation. The included dependent variables would be personal income per capita, amount of government subsidy, percentage of population living in metropolitan area, driving habits, availability of dealerships, and gas tax rate. However, at this point electric vehicle manufacturers are reluctant to release statewide sales figures to the public. Therefore this regression cannot be build until there is more readily available data on the independent variable.

References


