A Fuel Cost Comparison of Electric and Gas-Powered Vehicles

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Abstract
In this study, we estimate variable fuel costs and total energy consumption for grid-powered electric cars using eight-year forecasts of cost per kilowatt hour for US national data coupled with real data distributions derived by daily electronic tracking the performance of a single Nissan Leaf located in Texas. These fuel costs are estimated based on a stochastic driving distance, then costs are estimated for various fuel efficiencies, with predicted gasoline cost structure based on a simple, deterministic forecasting model.

We also use time series analysis of the average cost per gallon of gasoline and the same driving distribution to estimate the cost for several gas-powered cars. We incorporate two Design of Experiment factors that might be adjusted during the vehicle manufacturing process, estimated average miles per gallon for gas-powered cars operating under fixed conditions, and estimated average miles per kilowatt hour for electric cars operating under fixed conditions.

We develop a Monte Carlo simulation to analyze the cost differential between electric versus gas-powered cars. Using data from the simulation, we compare the fuel cost structure and provide some limited discussion of vehicle acquisition and residual costs.

1. INTRODUCTION
With the volatility of gasoline prices, the purchase of electric cars has become an attractive option to some, but understanding the actual variable fuel costs associated with such a purchase requires some analysis. Electric cars do not have real “miles per gallon” data associated with them, so cost ranges are not as easily understood.

With more constraints on energy resources and stringent regulations on emissions and fuel economy, the growth of energy efficient technologies – such as electric cars – is paramount [1]. When assessing the potential gains from energy efficient technologies, efficiency analysis must consider both the scale of energy flow and the technical component for improvement [2]. As part of this energy efficiency analysis, we must thoroughly analyze and compare the emissions, costs, and demand trade-offs [3-4].

The motivation for this study derives from the primary author’s ownership of an electric car 100% powered by the owner’s solar panel array. The problem of interest, one that is not well researched in the literature, is the combination of energy efficiency that make one car preferred over another for similar driving characteristics and uncertain but predictable fuel costs. This study is the only one of its type to examine the engineering trade-off considerations of average miles gallon (mpg) versus average miles per kilowatt hour (mpkWh) when considering cost for both gasoline and retail grid power. Finally, it is the absolute first study to use real data gathered from daily electronic tracking of electric vehicle information.

1.1. Background
The average price per gallon of gasoline for the United States has risen from $1.11 in May of 1992 to $3.47 in February of 2012, a 313% increase that has outstripped the geometric mean Consumer Price Index (CPI) inflation rate of 2.54% for this timeframe [5]. An increase commensurate with inflation should have resulted in gas prices of about $1.88. During the same span of time, the cost per kWh for electricity increased from .0821 cents to .1165 cents, only a 41% increase and more than 2 cents below the historical inflation rate expectation of the CPI [5]. The implication is that while refined gasoline products outpace the CPI inflation rate (possibly due to environmental and other production concerns), retail energy production has become increasingly a bargain. Figure 1 depicts the time series for both gasoline (regular unleaded, all formulations) and retail electrical power.

Figure 1. Time Series Analysis of Cost for Energy by Year

\[
y = 0.00698956x^2 - 27.86018297x + 27,763.48067419 \\
R^2 = 0.91339494
\]

\[
y = 0.00018894x^2 - 0.75470766x + 753.73283297 \\
R^2 = 0.85945190
\]

\[\text{Cost for Energy by Year, Left Axis: } \$/\text{gl, Right Axis: } \$/\text{kWh}\]
Figure 1 illustrates that the increases in the cost of gasoline have outstripped the increases in the cost of retail electricity.

The retail price of both gasoline and kilowatt-hour varies widely from state to state at any given point in time. Univariate distribution for two recent months are shown in both Figure 2 (gasoline) and Figure 3 (kilowatt hours). For gasoline, the median of the state “average price for regular unleaded” in July 2012 was $3.43 with a mean of $3.41 and a standard deviation of $.22 cents [5]. This included data from all 50 states plus Washington, DC. As Figure 2 depicts, the distribution has two outliers with gasoline prices above $4.00 per gallon (Alaska and Hawaii). Figure 3 reveals a single outlier (Hawaii). One should note that Washington state is one state that subsidizes electrical power utilization, which is not reflective of free market pricing. This data did not include Washington, DC due to differences in collection processes by the US Department of Energy.

Given the fast, non-linear increase in gasoline prices when compared to the increase in electrical prices, the attractiveness of electric cars becomes clear. It is likely that electric cars might provide significant savings in terms of variable fuel costs that would make them worth considering. Understanding the total costs of electric cars, however, is non-trivial. One cannot simply compare mpg between vehicles as in the traditional case, as true electric cars consume zero gas. Therefore, the function of most interest is the mpkWh, as understanding the fuel costs requires being able to compare mpkWh to mpg in some reasonable fashion. This necessity is addressed by this study.

2. MATERIALS AND METHODS

The research question for this study is straightforward: what mpg versus mpkWh factors make the purchase of an electric car or gasoline-powered car reasonable in terms of variable fuel costs given uncertainty in retail power? This research question addresses engineering efficiency trade-off considerations that might be reasonably assessable given fuel and electricity forecasting models. The significance of the research question is that it is the first to address variable cost mpkWh engineering considerations for electric vehicles given uncertainty of power costs.

2.1. Design of Experiments Factor 1

We gathered the cost per kilowatt hour (kWh) requirements of electric cars from real-world, time series data of a single Nissan Leaf located in Texas. While Texas certainly does not represent the entirety of the United States and is largely warmer than most states, the presence of heating/cooling elements for the batteries makes the consumption data reasonable for inference to similar regions. The distribution of interest was the daily mpkWh because it provides a mechanism for assessing comparative efficiency of vehicles when coupled with a time series analysis of cost per kWh. The univariate distribution of mpkWh (gathered electronically from Nissan Carwings™ technology) is shown in Figure 4 and is easily represented in Equation 1 by a beta distribution parameterized with a minimum, maximum, and the two regular shape parameters, mpkWh~B(3.96, 6.68, 1.76, 1.61), Kolomogorv-Smirnov (KS) statistic = .131, p=.972.

\[
 f(x) = \frac{(x - 3.96)^{1.76-1}(6.68 - x)^{1.61-1}}{B(1.76,1.61)(6.68 - 3.96)^{1.76+1.61+1}} 
\]  

(1)

In this equation, B is the beta function. The current reasonable capability for mpkWh based on this case is [4,7]; however, to assess the full range of potential engineering, we assess the mean mpkWh range of \{4, 6, 8, 10\} mpkWh.
2.2. Design of Experiments Factor 2

Miles per gallon is the second engineering characteristic of interest, especially given the advent of exceedingly efficient gasoline-powered cars. Some hybrid cars currently approach a combined 50 miles per gallon (city and highway) without using grid-powered electricity (e.g., the Toyota Prius). Such engineering feats must be used in comparative analysis. Due to current capability and possible near future capability, we assess the mean range of mpg as {30, 40, 50, 60}.

2.3. Stochastic Distribution 1

Another distribution of interest was the daily miles driven. Unlike other vehicles, electric cars cannot be driven without significant consideration of the recharging requirement. As an example, a 240-volt recharging event might restrict a driver for three to six hours, depending on the charge state and desired charge to be achieved. At 120-volts, the requirement is much more restrictive. Further, charger availability is a concern. Daily driving time should logically be restricted within certain bounds. Figure 5 depicts the actual daily usage for a single driver over six months as tracked by Nissan Carwings™.

2.4. Deterministic Distributions 1 and 2

As part of the simulation, it was important to have forecasts for both kWh costs and gasoline costs. As Figure 1 illustrates, some irregular events affect both markets, as noted by large deviations. While many forecast models were reasonable for estimating average gasoline prices per month, a simple monthly decomposition of 10 years of price data (May 1992 through March 2012) coupled with trend analysis and an AR1 component accounted for 98% of the variance. Eliminating the monthly component resulted in little loss, as the two primary variables (previous month prices and the forecast trend) still accounted for 97% of the variance with a median absolute deviation (MAD) of 4.5 cents per gallon. Assuming that this second model is reasonable enough for forecasting, one might use Equation 2 for forecasting the US average cost of regular gasoline ($Y_t$). Analysis similar to that performed for gasoline was conducted on electricity prices for the US ($K_t$), and the results were similar. Equation 3 contains only the previous month data and the trend captured 98% of the variance with a MAD of a fraction of a cent, 0.14 cents to be exact.

$$Y_t = 0.030 + 0.942 \times Y_{t-1} + 0.000716 \times t, \ R^2=.974$$  \hspace{1cm} (2)

$$K_t = 0.265 + 0.964 \times K_{t-1} + 0.000789 \times t, \ R^2=.983$$  \hspace{1cm} (3)

From Figure 1, it should be obvious that the two costs are correlated ($r=.91$), which helps explain the similarity between Equations 2 and 3.

2.5. Stochastic Simulation

Before developing the stochastic simulation, it was simple to provide deterministic estimates of cost differential per a fixed distance traveled given variable costs for gasoline and kWh as well as variable performance metrics for vehicles in terms of mpg and mpkWh. It was also relatively simple to evaluate an associated regression model. Such a planning tool is useful if estimates for all variables are available. Unfortunately, this state of nature is unlikely.

Figure 5 provides perspective of the current operating characteristics of an affordable electric car. The bimodal distribution correctly illustrates work versus non-work (e.g., vacation days) and miles traveled beyond 90 indicate that recharging was completed at some point during the day. For modeling purposes, however, the distribution of driving distance per day was modeled as a uniform distribution on [0,120] minutes to reflect the lack of knowledge regarding individual driving characteristics and improvements in performance that are likely to occur in the near term. The zero is an absolute bound while the 120 reflects a significant range challenge for affordable electric vehicles in the near future. It is also the point where the empirical distribution of Figure 5 shows only small, right-tail probabilities.
to be the case, so distributions based upon reasonable and real-world data provide a mechanism for evaluating this problem.

Figure 6 is a diagram of the simulation component of this study. Specifically, the simulation is a simple Monte Carlo analysis of the cost differential between electric versus gas-powered cars.

We wanted to have fairly tight estimates for total electric and total gasoline-powered costs. Specifically, we wanted to bracket eight year average costs within $100. We used Promodel software for the implementation of our Monte Carlo simulation model [6]. An initial 30 iterations using a baseline model (4 mpKwh and 30 mpg) resulted in an achieved confidence interval of about $60, indicating that 30 runs per iteration would be sufficient. Thus, we ran each 8-year (the estimated useful life of an electric car) experiment 30 times.

2.6. Verification and Validation
We conducted model verification and validation using qualitative and quantitative analysis. We used debugging procedures associated with ProModel, and we compared a priori and posterior distributions via hypothesis testing. Specifically, we tested the distribution of kWh.

To investigate validity, we analyzed the forecasts and distributions assumed and compared them to the posterior. The forecasts of the model were exactly as expected (no difference) from the deterministic equations, and the stochastic distribution (miles driven) was not statistically different from the distribution achieved via the simulation model (p>.05).

To be valid for model comparison, we needed to ensure that the random streams were identical across experimental conditions for the stochastic distribution of miles driven. To do so, we used the built-in random number seed function associated with ProModel. This seed saves the randomly generated number stream and uses it in all comparative models.
In order to assess whether the model was performing as required, we used variable indicators and debugging components of ProModel. By graphically displaying the flow, we were able to assess that the model was performing as expected (verification).

3. RESULTS
The simulation produced an average daily driving distance of 44.8 miles, which is to be expected given that the mean of the a priori uniform distribution was 45. The deterministic forecasts resulted in an average price for fuel of $7.59 per gallon over eight years, which assumes that the growth will follow historical trends. The maximum price was $11.92 in 2020. While this value seems high, it reflects a 15% steady state inflation rate per year, which is 4% higher than the inflation rate experienced from 2004 to 2008 (11%). In other words, the forecasting model assumes an accelerating increase in gas prices. The average cost per kWh was 16.33 cents for all eight years, while the maximum was 21.80 cents in 2020.

The results indicate that given the national estimates for fuel prices, electricity prices, and other assumptions, average electric car variable fuel costs based on kWh consumption are always lower than hybrid/gasoline-powered cars with miles per gallon from 30 to 60. The average costs per day experienced by the electric car operating at kWh of {4, 6, 8, 10} were {$1.83, $1.22, $0.91, $0.73} respectively. The average costs per day experienced by the gasoline/ hybrid vehicles operating at mpg of {30, 40, 50, 60} were {$11.31, $8.48, $6.79, $5.66} respectively.

Additional analysis using higher electricity rates and different forecasts will be conducted in future work. Furthermore, we do not address other additional costs of ownership such as maintenance and repairs, opportunity costs, residual value, depreciation, financing, and fees. Indeed, we would suggest that many of these factors cannot be estimated with reasonable precision, given that electric cars have only been available since 2011.

4. CONCLUDING REMARKS
In this short study, we demonstrate a largely deterministic simulation with a few stochastic components and Design of Experiment parameters. The initial analysis showed that the rate of gasoline cost increases was outstripping the rate of utility cost increases. A short simulation demonstrated that for the parameters selected and using forecasts for national averages, an electric car will universally be less expensive than a gasoline/hybrid through miles per gallon up to 60.

With this in mind, this initial analysis did not account for the entirety of life-cycle costs (operating costs, maintenance costs, replacement costs, etc.) associated with electric and gas-powered vehicles. Specifically, our cost comparison covers the cost of ownership over eight years because, at this time, the electric vehicle will need to be replaced. Gasoline-powered vehicles (with an internal combustion engine) generally last much longer (10 years is not uncommon). Therefore, further analysis should account for the longer lifetime of the gas-powered vehicle as well as additional life-cycle costs.

This study represents initial analysis which is ongoing. By the time of the conference, we will have improved the design of the simulation, expanded the parameters, and expanded the results section.

5. REFERENCES


Biographies
Lawrence V. Fulton currently teaches and researches for the McCoy College of Business Administration at Texas State University. He is a graduate of the University of Texas at Austin, earning a Ph.D. in Management Science and Information Systems. He also holds Master’s degrees in Health Administration, Human Resource Management, and Statistics.

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