2016

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Purchasing Efficiency Measurement of Selected Electric Vehicles in the United States Utilizing Data Envelopment Analysis (DEA)

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Abstract

Consumers today face an ever-increasing number of choices when deciding what purchases to make. Nowhere is this more apparent than the market for vehicles. Many factors affect a consumer's ultimate decision of what vehicle to purchase or lease. Further, electric vehicles present the consumer with additional unique considerations. This study evaluates the decision making process used by consumers in purchasing an electric vehicle. The decision making units (DMUs) used in this research include manufacturer's suggested retail price (MSRP), range in miles, miles per gallon equivalent (MPGe), cargo space in cubic feet, and charge time in hours. These variables are factors commonly of interest to consumers. Further, Data Envelopment Analysis (DEA) has been applied to determine the relative efficiencies of twelve consumer electric vehicles currently on the market; eight electric vehicles were found to be efficient choices and four were found to be inefficient. Included in this study are suggestions on how auto manufacturers can improve the efficiency of vehicles deemed inefficient.

Introduction

An electric vehicle (EV) is a form of alternative energy transportation. It is "alternative" in the sense that it is not powered by gasoline, the standard fuel source for most modern consumer vehicles. Compared to their gasoline counterparts, EVs trade gas tanks for battery packs and internal combustion engines for electric motors. They may seem like a modern concept, but their history reaches back nearly to the dawn of automobiles. In the early days of loud, cumbersome, and unreliable internal combustion engines, people looked to the electric car to revolutionize transportation. Thomas Davenport built the first electric vehicle (EV) in 1834. From that time, technological advances have led EVs to outpace gasoline powered vehicle sales: EVs held a 38% market share in 1900 compared to 22% for the gas powered vehicle; steam powered vehicles account for the remaining 40%. Due to lack of battery technology, the electric car lost traction and gasoline became the preferred fuel source. More EV research was done in the 1960's as a result of the space program. A recently developed class of vehicles combines the benefits of both power sources to achieve short refueling times, long driving range, and high fuel efficiency. This combination has led hybrid-electric vehicles, or "hybrids," to outsell "pure" EVs (Lerner & Lerner, 2008). However, improved battery technology has also driven a resurgence of "pure" EVs. Sales of street legal EVs were fueled by improvements in technology and incentives between 2008 and 2015; 373,000 have been sold in the United States, accounting for 38% of the "plug-in" electric vehicle fleet worldwide (Cobb, 2015). According to Electric Drive Transportation Association's statistics, the total electric market share of cars (including hybrids, plug-in hybrids, extended range and battery) sold in the United States ranged from 2.23% to 3.47% from 2007-2016. There are several benefits to purchasing an EV. First, the design of EVs allows for little or no energy use when coasting.

Also, instant torque is available to the driver. Taking into account the need to create electricity to charge them, EVs are still considered more efficient than their gas counterparts (Lerner & Lerner, 2008). However, other factors to take into consideration are that, in general, electric vehicles have less range than gasoline-powered cars, are more expensive than their gasoline-powered equivalents and require expensive charging stations and/or extended periods of time to recharge. As electric vehicles make a comeback, there is a need to evaluate market offerings in this expanding industry. The efficiency of various EVs on the market should be studied to increase adoption of alternative energy transportation, to remain competitive against other means of transport, and to better inform consumers.

The goal of this study is to evaluate plug-in electric vehicles currently on the market in the United States as of 2015, and to determine which one(s) produce(s) the highest DEA efficiency. DEA analysis is an ideal tool for consumers since it measures how efficient a purchase is. Efficiency in this context is defined as how efficiently the consumer's dollars (inputs) are converted into performance and utility metrics (outputs).

A number of variables are of concern to the average automobile consumer. The major input for consumer's purchasing an EV is the purchase price, for which the standard measure is the manufacturer's suggested retail price (MSRP) of the vehicle. Outputs are the vehicle's range, miles per gallon equivalent (MPGe), cargo space in cubic feet, and charging time in hours. Given these variables, DEA analysis determines how efficient the purchase of a given electric vehicle is in relation to other vehicles available. Analyzing this market shows which vehicles efficiently deliver value to the consumer and how inefficient vehicles can improve their standing. These measures of efficiency provide advice to manufacturers for product improvement and consequentially increase the adoption of alternative energy vehicles.

The paper includes a review of the literature relevant to this study. A brief discussion of DEA modeling and preliminary analysis of data is provided. The final results and discussions are demonstrated utilizing the DEA model.

Literature Review

A review of published literature found that efficiency of the available options when purchasing an electric car has not been thoroughly studied. A small selection of studies uses the DEA model to compare automobile efficiency. Of the two published works found, only one source evaluated alternative energy vehicles. The Uppsala University Department of Economics performed a study of vehicle efficiency using DEA analysis in 1997. This study, conducted by Papahristodoulou (1997), focused on 121 European Fossil Fueled vehicles with statistics from a German automotive magazine. The study grouped the vehicles into three categories based on engine volume and evaluated the efficiency of each vehicle relative to others in the same group. Input and output variables selected for evaluation included MSRP, cost of ownership (including fuel and insurance), total interior volume, cargo area volume, engine horsepower, acceleration time (0-60 mph), depreciation after one year or ownership, top speed, and wheelbase length. Much can be learned from the structure of the DEA analysis employed. However, the vehicles from this 1997 comparison are now outdated.

Partovi & Kim (2013) utilized DEA analysis to compare vehicles in five categories in order to find the most efficient vehicle relative to fuel efficiency and carbon emissions. The five categories of vehicles were based on the type of fuel the vehicles consumed. Categories were diesel, gas, hybrid gas/electric, fully electric, and hydrogen vehicles. Inputs for DEA analysis included the annualized MSRP, fuel cost, and maintenance cost. Outputs were carbon footprint, range (based on MPG/fuel tank size), horsepower, acceleration time, and cargo volume. Although this study does include electric vehicles, many options were either not available for purchase in 2013 or excluded from study. Only four electric vehicles were compared and some data may no longer be accurate. Also, one of the four vehicles compared was the Chevrolet Volt, which is equipped with a gasoline-powered generator to extend the range of the vehicle; this presents difficulty in comparing it with fully electric peers.

Numerous studies on electric vehicles identify several

key consumer preferences. When deciding whether to purchase an electric vehicle or gas-powered vehicle, consumers valued certain characteristics. Usage patterns indicate that 70% of all travel personal automotive travel never exceeds 100 miles of driving per day. Thereafter, trips beyond 100 miles in one day are statistically infrequent (Tamor, Gearhart & Soto, 2013). A separate study confirms this finding by data collected from 484 instrument equipped vehicles. The study also indicated that automobile consumers have a poor understanding of fuel and range of electric vehicles and their own usage habits. As a result, potential consumers have "Range Anxiety "when selecting an electric vehicle; this is based on the fear of running out of charge when driving (Pearre, Kempton, Guensler, & Elango, 2011). Therefore, from consumers' perspectives, the most important feature of an EV is that it is range sufficient and can meet or exceed their daily mileage needs.

Consumer studies indicate concerns with the charging time of electric vehicles. Research into consumer preferences indicates that customers demand faster charge times. This preference results from a consumer who is used to gasoline vehicles comparing EV charging with filling up at a gas station (Pearre, Kempton, Guensler, & Elango, 2011). Although such studies indicate consumers prefer a faster charging time, operational statistics indicate the opposite. When patterns of EV usage and charging were tracked, studies found that a majority of vehicle charging takes place during the workday or at night, as the consumer sleeps (Speidel & Bräunl, 2014). As long as a vehicle can fully charge in 6-8 hours, it can be deemed operationally "efficient" despite consumer beliefs. In practical applications, electric vehicles would not require the use of charging stations away from home/work, unless traveling beyond the vehicle's range. Such trips are found to only occur on rare occasions, and the target market in the United States for electric vehicle adoption is a two-car household with a gas-powered vehicle available for such long trips (Tamor & Milacic, 2015). For commercial applications as fleet vehicles, the same logic applies; charging would likely occur during non-work hours when vehicles sit idle for long periods of time, and "fast charging" is not operationally necessary.

DEA Model

Data Envelopment Analysis (DEA) is a useful tool to compare a uniform set of entities. The DEA model was first applied by Michael Farrell in 1957, then further popularized and named by Abram Charnes, William W. Cooper and Eduardo Rhodes in the late 1970's (Darity, 2008). This model is extremely useful to estimate efficiency when multiple inputs are used to produce various outputs, since it can operate independent of scale or specific variables. The DEA model analyzes the relative performance of Decision Making Units (DMUs). DEA can still model efficiency in absence of specific distributions or inputs; this allows the DEA model to be applicable to a wide variety of situations. For the study presented here, the DEA model is able to be applied by treating each electric vehicle as an individual Decision Making Unit. This research could be further extended to any variety of vehicle performance inputs and outputs relevant to consumer decision making.

The efficiency ratios in the DEA model are an advanced version of a multifactor productivity ratio. The DEA formula compares the productive efficiency of each particular unit relative to other DMU's. DEA analysis has numerous advantages that aide in analyzing the collected data. The DEA model allows for the comparison of multiple inputs and outputs on independent scales; this process reveals relationships between entities that remain hidden when utilizing other statistical methods. Units are assigned an efficiency percentage allowing us to identify inefficient units. Units that achieve a score of 1.00 or 100% are efficient, and units scoring less than 1.00 or 100% are inefficient. Results from DEA analysis also allow us to identify sources of inefficiency in each decision-making unit and corrections that can be made to remedy the inefficiency. The objective function of the DEA model is set up to maximize efficiency "Ee" for the given decision making unit. The variable "u" represents the output of each DMU. The variable "v" represents input of each DMU. Variables "O" and "I" represent the weights of the respective inputs and outputs. Variable "M" expresses the total number of outputs being compared and Variable "N" represents the total number of inputs being compared. This notation demonstrates

that the objective function can be extended to different quantities of input and output categories subject to the needs of analysis.

Objective Function:

To solve the objective function using a linear programming model, the original objective function must be translated into a linear function. When expressed in a linear form, it is possible to use Linear Program Solver tools such as Microsoft Excel Solver to obtain a solution. Using the solver to change the weights expressed

$$(MAX)\ E_e = \frac{u_1O_{1e}+u_2O_{2e}+\ldots+u_MO_{Me}}{v_1I_{1e}+v_2I_{2e}+\ldots+v_NI_{Ne}}$$

as "O" and "I" obtains the optimal solution for each DMU. This transformation results in the numerator of the objective function expressed as a linear equation to be maximized, and the denominator becoming a constraint where it sets up to equal to 1. Therefore, the linear expression of the objective function would be:

Another set of constraints ensures that the efficiency of all the decision-making units will not be greater than 1. Variable "k" represents the index of decision making units being evaluated. Capital "K" represents the last DMU. The original format of the constraint is the ratio of the weighted output over weighted input

$$(MAX)\ E_e = u_1O_{1e}+u_2O_{2e}+\ldots+u_MO_{Me}$$
$$(S.T.)\ v_1I_{1e}+v_2I_{2e}+\ldots+v_NI_{Ne}=1$$

with a nonlinear format, which is needed to transform into a linear format just like the objective function.

Constraint Function:

The equivalent linear equation would say that the difference between the weighted output and the weighted input should be less than 0, which:

To ensure the optimal results, the DEA model also requires that the quantity of DMU's exceeds two times the total number of

inputs and outputs being evaluated. This constraint expresses the

$$\frac{u_1O_{1k}+u_2O_{2k}+\ldots+u_MO_{Mk}}{v_1I_{1k}+v_2I_{2k}+\ldots+v_NI_{Nk}} <= 1 \quad k=1,2,3\ldots,K$$

minimum quantity of DMU's to be selected given the number of inputs and outputs being evaluated.

$$(u_1O_{1k}+u_2O_{2k}+\ldots+u_MO_{Mk})-(v_1I_{1k}+v_2I_{2k}+\ldots+v_NI_{Nk})<=0 \quad k=1,2,3\ldots,K$$

Sample (DMU) Quantity Constraint: $K >= 2(N+M)$

Data and Preliminary Data Analysis

Variables were chosen based on the previous studies by Papahristodoulou (1997), Partovi & Kim (2013), and other studies relating to the purchasing of vehicles and consumer demands specific to electric vehicles. Here are the major inputs and outputs.

Price: The most direct input when purchasing a vehicle is its price. While what consumers actually pay varies, based on incentives and their negotiating skills, Manufacturer Suggested Retail Price (MSRP) is the standard base measure of a vehicle's price.

When buying a vehicle, consumers have numerous feature considerations to make, which are the output variables of such a purchase.

Cargo Space: It is a common decision variable. Usually it is the storage capacity of the vehicle, measured in cubic feet, which does not impede on passenger volume.

Fuel efficiency: An important measure for most buyers, EVs measure this metric in MPGe. As stated by Green Car Reports, "(MPGe) stands for "miles per gallon (of gasoline) equivalent. Those MPGe figures have mystified many potential plug-in electric car buyers, but they remain the primary way of comparing energy efficiency by internal-combustion and electrified vehicles" (Edelstein, 2015). It is calculated as follows: The Environmental Protection Agency (EPA)

determined that 1 gallon of gasoline contains 33.7 kilowatt hours of electricity (kWh). MPGe is based on the kWh the vehicle uses to drive 100 miles. The Volkswagen e-Golf for example, uses 29 kWh/100 miles. The calculation is: 100 miles / (29kWh/33.7kWh) = 116 MPGe (fueleconomy.gov). MPGe is a commonly used way of measuring vehicle efficiency, which is correlated with charging costs. Generally, the higher the MPGe, the less the vehicle will cost to charge.

Range: Measured in miles, it is how far the vehicle can go before running out of charge. It is a result of efficiency and battery size.

Charge Time: Reflective of how long it takes to charge the vehicle using a 240V socket, the highest voltage outlet commonly available. Consumers generally prefer a lower charge time. As such, charge time has been treated as an input variable. Some EVs possess a "quick-charge" feature, which allows the vehicle to be charged to 80% capacity in approximately 30 minutes. This research considers charge time as the time necessary to charge the vehicle from "empty" to maximum battery capacity.

Given multiple dimensions and complexity of comparing so many EVs, making such an expensive purchasing decision is often daunting. Data was collected from online sources. Multiple websites were used, including manufacturer sites (Ford.com, Kia.com, etc.), automotive publications, namely Car and Driver and the U.S. Government's site, FuelEconomy.Gov. It was also attempted that data for each variable was collected from a single source to ensure consistency. Data was cross-checked with other sources to ensure accuracy.

Results

This study utilizes DEA analysis to measure the efficiencies of twelve electric cars available in the United States. Microsoft Excel with a solver add-on has been used for computations. The range of possible efficiencies is between 0 and 1.00. If a vehicle's efficiency was measured to be 1.00, then the vehicle is said to be efficient. If efficiency is found to be less than 1.00, the vehicle is said to be inefficient. Eight electric vehicles were found to be efficient, and four were found to be inefficient. The results are shown in Table 2.

Recommendations

Computations from the Excel solver include a shadow price for each decision making unit analyzed. The shadow

Table 1

Decision Variables	
Inputs	**Outputs**
Manufacturer's Suggested Retail Price (MSRP)	Range (Miles)
Charge Time (Hours)	Miles Per Gallon Equivalent (MPGe)
	Cargo Space (Ft^3)

price measures how inefficient decision making units could become efficient, with reference to efficient decision making units. Using the shadow price enables computation to find what variables have to change, and by how much, for an inefficient vehicle to become efficient. Please refer to Table 3 to see the recommended changes. Recommendations are as follows:

The Fiat 500 EV is inefficient due to its cargo space, an output and price, and charge time inputs. Cargo space should be increased from 7 to 17.91 cubic feet of cargo space; this would require more than doubling the Fiat's cargo capacity. MSRP should be reduced from $31,800 to $30,544.19, and charge time should be reduced from 4 to 3.84 hours. These changes would

Decision Variables Table

Table 1

		Output 1	Output 2	Output 3	Input 1	Input 2
Make/Model	DMU #	Range (Miles)	MPGe	Cargo Space (Ft^3)	MSRP	Charge Time (Hours)
Tesla Model S-85	1	265	89	26	$80,000	12
Nissan Leaf S	2	84	114	24	$29,010	8
Nissan Leaf SE	3	84	114	24	$32,100	5
Fiat 500EV	4	87	116	7	$31,800	4
Chevy Spark EV	5	82	119	11	$25,170	7
Ford Focus Electric	6	76	105	14	$30,045	3.6
Kia Soul EV	7	93	105	19	$31,950	4
BMW i3	8	81	124	15	$43,350	4
Mercedes B-Class	9	87	84	22	$41,450	3.5
Volkswagen e-Golf	10	83	116	17	$28,995	3.7
Smart Four-Two EV	11	68	107	8	$25,000	6
Mitsubishi i-MiEv	12	62	112	13	$22,995	7

increase the Fiat's efficiency rating from 0.9605 to 1.00.

The Ford Focus Electric is inefficient because of its cargo space, MSRP, and charge time as well. The Focus' cargo space should be increased from 14 to 15.70 cubic feet. The vehicle's MSRP should drop from $30,045 to $26,907.59. Charge time should be reduced from 3.6 hours to 3.38 hours. Following these suggestions would

increase the Focus' efficiency rating from 0.9377 to 1.00.

The BMW i3 is inefficient due to its range and cargo space, outputs and MSRP, and charge time inputs. The i3's range should be increased from 81 to 88.72 miles and cargo space should be increased from 15 to 18.1724 cubic feet. Also, it is recommended that MSRP be reduced from $43,350.00 to $30,994.66, and charge time should be dropped from 4 hours to 3.96 hours, (an almost insignificant sum). Implementing these changes would increase the i3's efficiency rating from 0.9888 to 1.00.

The last inefficient vehicle is the Smart For-Two EV. It is inefficient because of its cargo space, MSRP, and charge time. The Smart's cargo space should be increased from 8 to 12.70 cubic feet. It is recommended that MSRP be reduced from $25,000.00 to $23,514.76, and charge time should drop from 6 to 5.64 hours. Implementing these suggestions would increase the Smart's efficiency rating from 0.9406 to 1.00.

Recommendations to increase efficiency

Table 1

Make/Model	Efficiency Score	Conclusion
Tesla Model S-85	1	efficient
Nissan Leaf S	1	efficient
Nissan Leaf SE	1	efficient
Fiat 500EV	0.9605	inefficient
Chevy Spark EV	1	efficient
Ford Focus Electric	0.9377	inefficient
Kia Soul EV	1	efficient
BMW i3	0.9888	inefficient
Mercedes B-Class	1	efficient
Volkswagen e-Golf	1	efficient
Smart Four-Two EV	0.9406	inefficient
Mitsubishi i-MiEv	1	efficient

Conclusion

In this study, DEA analysis was used to determine the efficiencies of twelve electric vehicles. Of the twelve vehicles studied, eight are efficient choices, while four are inefficient. This study allows consumers to readily compare their options when buying an electric vehicle. Results of this study will enable consumers to make an efficient purchasing decision with priority to their specific needs. Manufacturers can also benefit from this study; by making the recommended changes to their vehicles, manufacturers can increase their competitiveness relative to other offerings.

The limitations of this study involve

Table 1

Make/Model	Range (Miles)	MPGe	Cargo Space	MSRP	Charge Time
Fiat 500 EV	87	116	17.91	$30,544.19	3.84
Ford Focus Electric	76	105	15.70	$26,907.59	3.38
BMW i3	88.72	124	18.17	$30,994.66	3.96
Smart For-Two EV	68	107	12.70	$23,514.76	5.64

meeting specific consumer's needs. If the consumer's usage pattern of the vehicle involves overnight charging and never exceeds the vehicle range in a single day of driving, charge time may be less critical. Some consumers may live in urban environments where space commands a premium. Therefore, buyers may prefer smaller vehicles such as the Fiat 500 EV, BMW i3, or the Smart For-Two EV. Since the automotive purchasing environment in the United States involves negotiation, it is possible for urban consumers to bargain for the efficient price listed in Table 3.

Further, the Tesla Model S, Mercedes B-Class, and BMW i3 are classified as luxury or near-luxury vehicles. Some of their features were not quantifiable for the purpose of this study. Due to their added amenities and comforts, some consumers may consider them more efficient when compared to non-luxury vehicles. Despite the fact that luxury amenities were not quantified, the Tesla Model S and Mercedes B-Class were deemed efficient relative to all EV's available. Therefore, if either the Tesla or Mercedes is within the consumer's budget, it would be a more efficient purchase than a BMW i3 in the luxury category.

Other factors that may be valuable to some consumers were not included in this current study. Acceleration, measured by 0-60 mph time in seconds, is a common metric of vehicle performance;

this was not included, as the purpose of this study was to evaluate utility and practicality rather than performance. Long-term maintenance costs were not included due to limited data availability. Further studies would need to be designed to include these measures.

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