

Comparing Total Cost of Ownership of Battery Electric Vehicles and Internal Combustion Engine Vehicles

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Abstract

The technological advance of electrochemical energy storage and the electric powertrain has led to rapid growth in the deployment of electric vehicles. The high cost and the added weight of the batteries have limited the size (energy storage capacity) and, therefore, the driving range of these vehicles. However, consumers are steadily purchasing these vehicles because of the fast acceleration, quiet ride, and high energy efficiency. The higher pack-to-wheel efficiency and the lower energy cost per mile, as well as the lower expense for maintenance and repair, translate to operating savings over conventional vehicles. This

paper compares battery electric vehicles with internal combustion engine vehicles based on the total cost of ownership. It is seen that the higher initial cost of electric vehicles can be recovered in as little as 5 years. This is especially true for electric vehicles with shorter driving ranges. Specifically, a vehicle with an electric driving range under 200 miles may achieve cost parity with an equivalent internal combustion engine vehicle in 8 years or less.

Keywords: Total cost of ownership, Battery electric vehicle, Electric powertrain, Cost parity, Favorability

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Acronyms and Abbreviations

ADT	Annual Distance Traveled
AOC	Annual Operating Cost
AT	Alternative Transportation
AYO	Average Years of Ownership
BEV	Battery Electric Vehicle
BMS	Battery Management System
CAFE	Corporate Average Fuel Economy
DC	Direct Current
DMV	Department of Motor Vehicles
DOE	Department of Energy
DR	Driving Range
ECU	Engine Control Unit
EIA	Energy Information Administration
FI	BEV Favorability Index
GHG	Greenhouse Gas
HC	Home Charger
HOV	High-Occupancy Vehicle
IC	Initial Cost
ICCT	International Council on Clean Transportation
ICEV	Internal Combustion Engine Vehicle
MPG	Miles per Gallon
MPGe	Equivalent Miles for BEV from the Energy Content of a Gallon of Gasoline
MR	Annual Maintenance and Repair Cost

MSRP	Manufacturer Suggested Retail Price
NHTS	National Household Travel Survey
NPV	Net Present Value
OEM	Original Equipment Manufacturer
SUV	Sport Utility Vehicle
TCO	Total Cost of Ownership
UBS	Union Bank of Switzerland
UF	Utility Factor
VP	Vehicle Price
YTCP	Years to Cost Parity

1. Introduction

Internal combustion engine vehicles (ICEV) have seen incredible advances over the last century and have served as a cornerstone in transit. Their ever-expanding utility and consumer demand have led to a massive rate of consumption of petroleum fuels with the commensurate output of greenhouse gases (GHGs) and emissions. Societies and governments have sought to reduce these byproducts by switching to zero-emission vehicles such as battery electric vehicles (BEVs). These electric vehicles are now approaching a mass deployment that can be sustained only if average consumers are convinced that their cost of commitment to a greener vehicle with more enhanced features (e.g., faster acceleration, quiet operation, lower operating cost, etc.) can be recouped within a reasonable time of ownership.

The recent and ongoing development of battery technology, accompanied by automated mass production, has led to a lower-cost electric powertrain, thereby shrinking the premium price that is paid upfront for the purchase of BEVs. The lower operating cost, derived from lower energy and maintenance costs, accelerates the recovery of this price differential within the typical ownership period. This paper reports on a study to determine the time required to achieve cost parity between the BEV and the ICEV.

The total cost of ownership (TCO) method has been widely employed to study and compare the economy of vehicles comprehensively and transparently which enables rational decisions by customers, manufacturers, as well as policymakers. In the last decade or so, new approaches to recalculate the TCOs of different new powertrain types, e.g., electric vehicles, have been proposed as the deployment of renewable energy vehicles has dramatically grown in global markets. The term TCO was defined by Ellram in the 1990s (Ellram 1993, Ellram 1995) and first applied by Delucchi and Lipman to estimate the lifetime cost of an electric vehicle in 2001 (Delucchi and Lipman 2001). Roosen et al. reviewed TCO models published prior to 2015 in (Roosen, Marneffe et al. 2015). These works were customer-oriented and mainly looked at energy efficiency, lower running costs, policy subsidies, and incentives, all of which help to offset the purchase price premium that is paid for electric vehicles (Elgowainy, Rousseau et al. 2013, Lebeau, Lebeau et al. 2013, Macharis, Lebeau et al. 2013, Dumortier, Siddiki et al. 2015, Lebeau, Macharis et al.

2015, Rusich and Danielis 2015). Based on these studies, Wu et al. presented a probabilistic method to incorporate the stochastic nature of input parameters for TCO calculation on selected vehicle classes (Wu, Inderbitzin et al. 2015). Later, Letmathe and Soares compared the TCO of a few prevailing BEV classes that take up substantial market shares in Germany (Letmathe and Soares 2017). They further divided the TCO into customer-oriented and society-oriented categories by considering environmental impacts such as greenhouse gas emissions (Baumgärtner and Letmathe 2020). Despite the variances of data sources and methodologies, a common conclusion drawn from existing TCO studies is that electric vehicles are more expensive than conventional vehicles without federal/state policy supports with a potential to reach cost parity in the near future. However, most of these previous works are based on limited BEV classes, such as compact vehicles and sedans, with short-mid electric driving ranges less than 300 miles, due to the lack of data availability (Bjerkar, Nørbech et al. 2016, Bubeck, Tomaschek et al. 2016, Hagman, Ritzén et al. 2016, Lévy, Drossinos et al. 2017, Breetz and Salon 2018, Danielis, Giansoldati et al. 2018, Palmer, Tate et al. 2018, Simeu and Kim 2018, Hamza, Laberteaux et al. 2020, Hsieh and Green 2020, Scorrano, Danielis et al. 2020).

This work contributes to the TCO studies by comparing BEVs and ICEVs in the US market. Based on the latest battery pack data calculated from the BatPaC 4.0 package (Nelson, Ahmed et al. 2019) and public data, the TCOs for BEVs covering 1,000 to 2,500 kg curb weights and 150 to 450 miles driving range are estimated and compared with comparable (weight and power basis) ICEVs. The cost parity periods for different BEV classes are calculated for different vehicle operating scenarios. A broad spectrum of BEV curb weights and driving ranges is established for a systematic TCO study to compare with ICEVs. Furthermore, by taking into account the vehicle performance features such as acceleration and environmental impacts from greenhouse gas emission, an overall evaluation of BEV favorability over ICEVs with respect to curb weight and electric driving range is conducted. More importantly, the self-consistent method introduced in this work is transferrable to a broader range of energy-mass correlated calculations or modeling.

2. Method

This section describes the method used to compare equivalent BEVs with ICEVs and determine the number of years needed for the owner to recoup the higher purchase price of BEVs. The method starts by selecting a class of ICEV based on its curb weight. The vehicle's price, power rating, miles per gallon, weights, and costs of its major components (engine, transmission, exhaust system, etc.), are correlated from publicly available data (see Section 2.2.1). A corresponding BEV is then represented with substitutions of components, including their contribution to the vehicle mass and cost. As illustrated in Fig. 1, the BEV price is calculated by subtracting the ICE powertrain costs from an equivalent ICEV price obtained from MSRP data and adding the electric powertrain costs. Likewise, the BEV curb weight is computed in the same way by deducting the ICE powertrain weight from an ICEV curb weight and adding the powertrain weight of an equivalent BEV. All other components (*i.e.*, chassis & body, wheels, interior, and other auxiliary components) are kept constant and equivalent between the two vehicle types. By doing this, we assume the same cost margin from original equipment manufacturers (OEMs) for equivalent BEV and ICEV classes. The detailed model description and calculation algorithm are discussed in Section 2.3.

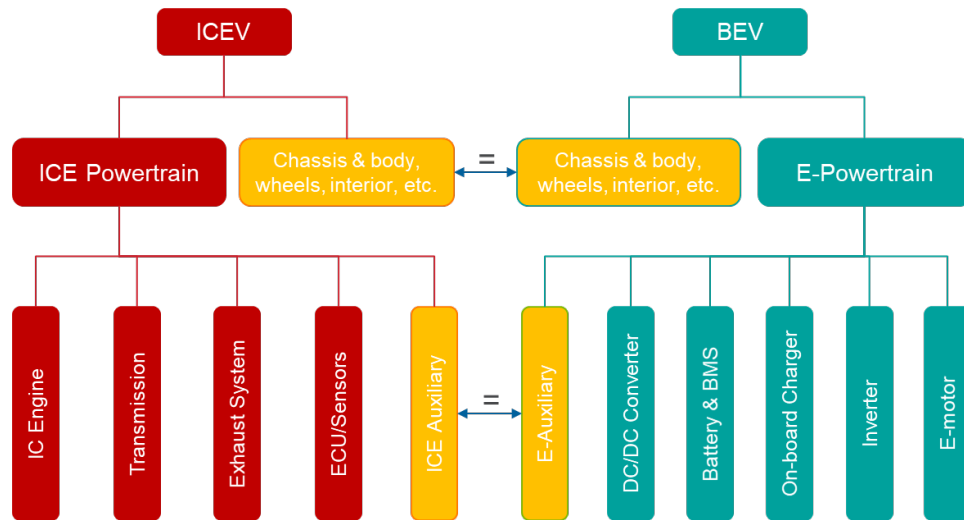


Fig. 1. Schematic of the assumptions made for an ICEV and the equivalent BEV weight and cost calculation.

In terms of operating costs, the BEV offers a much lower energy cost per mile than that incurred with current gasoline prices in the U.S., and even more so in most other nations. The fewer moving parts of the BEV also allow for a lower maintenance cost. Other cost factors such as vehicle registration, insurance, and cost of alternative transportation are also factored into the ownership cost comparisons between the ICEV and BEVs (Section 2.2.3). The annual cost saving is then used to determine the number of years required to offset the higher purchase price of BEVs, and hence the period required for cost parity based on the TCO between BEVs and ICEVs (Section 2.3).

2.1 Total Cost of Ownership

The TCO of a vehicle estimates the costs during the ownership period of the product, which can be studied with respect to environmental factors (amount and location of greenhouse gas emissions), societal factors (e.g., a path to greater electronic connectivity, i.e., automated mobility, etc.), and consumer interests such as initial purchase price, operating costs, performance, amenities, etc. This work focuses primarily on the vehicle mass, price, and cost of ownership. Unlike other works defining TCOs by accumulative driving mileage (Simeu, Brokate et al. 2018), this work uses a TCO in terms of operating years to calculate the cost parity period calculation.

The TCO includes the one-time purchase cost of the vehicle (and accessories or services), and all operating costs associated with its ownership. For comparison purposes, all future costs were converted into the net present value (NPV) at the time of vehicle purchase. Therefore, the NPV of TCO is written as

$$TCO_{NPV} = IC + \sum_{n=1}^N \frac{AOC}{(1+i)^n} \quad \text{Eq. (1)}$$

where the initial cost (IC) equals its NPV and the annual operating costs (AOC) were discounted by an annual rate, i , for an ownership period of N years. The initial cost and operating cost are further written as

$$IC = VP + RegI + HC \quad \text{Eq. (2)}$$

$$AOC = MR + Ins + Fuel + RegA + AT \quad \text{Eq. (3)}$$

where the initial cost is the sum of the vehicle price (VP), initial registration fees (RegI), and home charger cost (HC) for electric vehicles. The annual operating cost (AOC) includes the maintenance and repair cost (MR), insurance premium (Ins), fuel consumption cost (Fuel), annual registration fee and any additional state fee for BEVs (RegA), and the alternative transportation costs (AT) for any replacement vehicle needed because of the limitations of BEV driving range or charging time. Here, the maintenance and repair, fuel consumption, and alternative transportation costs per year are also functions of annual distance traveled (ADT). It should be noted that this study evaluates the cost competitiveness during a vehicle's normal operation over a wide span of ownership from 3 to 13 years. This study excludes vehicle resale/depreciation and battery replacement costs which usually occur in the later stage of ownership. On the other hand, local incentives/subsidies and value-added taxes were also not incorporated in the model due to policy variations between markets. Although financial supports play an essential role in the early stage of the BEV market, they will disappear as BEV sales continue to increase. Also, no driving pattern variance is assumed during operation. Since the home charger and alternative transportation costs are highly user-dependent, we defined a baseline TCO (TCO_{base}) to exclude these two items, but present a case study with those items included.

2.2 Data Sources and Baselines

An analysis of the TCOs for ICEVs and BEVs, which are differentiated by their types of powertrain, is conducted in this subsection. To make a valid estimation of the initial purchase cost of a mass-produced vehicle, it is assumed that the weight and cost of non-powertrain parts of an equivalent BEV and ICEV are the same. The non-powertrain components include the chassis and body, wheels, interior, comfort, and safety (Fig. 1). This assumption reasonably simplifies the cost parity analysis between different vehicle classes, which is based on the cost breakdown from the Union Bank of Switzerland (UBS) report (UBS 2017) and applied in other work (Hamza, Laberteaux et al. 2020).

The first two parts of this subsection are focused on modeling the prices of ICEVs and BEVs, respectively, using the powertrain costs from available data. Generally, the price of a vehicle and the main powertrain components can be approximated concerning the vehicle curb weights. Therefore, we categorize the comparison study into different vehicle curb weights ranging from 1,000 to 2,500 kg, which covers most light-duty cars, trucks, and sport utility vehicles (SUVs) on the market. For BEV models, we further classify their driving ranges, from 150 to 450 miles, with corresponding usable battery energies. All vehicle price, curb weight, and peak power data were obtained from vehicle official websites and the Edmunds database (Edmunds 2020), while the data on powertrain component weights and OEM costs are sourced from reports of A2Mac1 (A2MAC1 2020), the UBS (UBS 2017), the U.S. Department of Energy (DOE) (DOE 2020), the International Council on Clean Transportation (ICCT) (ICCT 2019) and public auto-search engines (Jegs 2018, Carparts 2020). The last part of this subsection models the rest of the cost items in the TCO for vehicles of different powertrains based on the estimated vehicle purchase costs in the first two parts of this subsection as well as the public data surveyed. Linear correlations were used in the model unless more complex correlations offered a significantly better fit.

2.2.1 The ICEV Powertrain

The ICE powertrain consists of an internal combustion engine, transmission, exhaust system, engine control unit (ECU)/sensors, and other auxiliary components, as shown in Fig. 1. This section models the component-wise ICEV powertrain weight and OEM cost. Based on a selection of ICEV data covering a wide range of models on the market, the engine power of the vehicle can be correlated to the vehicle curb weight using a power-to-weight ratio ranging from 58 to 264 W/kg as shown in Fig. 2, depending on the category of the vehicle. The ICEV powertrain data cover compact, sedan, SUV and pickup truck models, as detailed in Table S1, S5, S6 and S7. Note that a racing model outlier (*i.e.*, Ferrari 458, marker “x” in Fig. 2) is included as a demonstration of the data range variation only, but it is not used for correlation fitting.

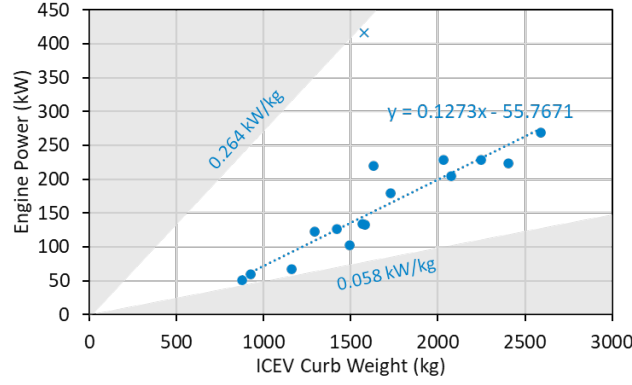


Fig. 2. The engine power-vehicle curb weight correlation and the power-to-weight ratio range of selected market ICEV (Edmunds 2020). The ‘x’ on the figure represents data from an outlier (Ferrari 458), which was not used in the fit. [Data from SI Table S1]

The ICEV powertrain cost is mainly contributed by the engine, transmission, exhaust system and ECU/sensors. The costs of the other powertrain components are marginal and thus are grouped as “ICE Auxiliary”. We modeled these ICE powertrain component OEM costs based on available data sources. The internal combustion engine cost (C_{Engine}) using the following correlation (Jegs 2018).

$$C_{Engine}(\$) = 0.174 \times Power(kW)^{1.808} \quad \text{Eq. (4)}$$

The engine cost and power source data are shown in Fig. 3 (a), from which 25% was discounted to estimate OEM cost. Due to limited data sources for ICEV transmissions, the transmission costs are from the latest U.S. Department of Energy’s Benefits Analysis using Autonomie modeling (Stephens, Birky et al. 2017). Then, we use an empirical correlation between the transmission cost and the vehicle curb weight to derive the dollar per vehicle curb weight values, which range from \$0.316/kg to \$1.487/kg, as shown in Fig. 3 (c) and Table 1. The derived ICEV powertrain and the costs of its main components are listed in Table 1. The exhaust system and ECU/sensor costs take up a small portion of the total powertrain cost and vary little with engine power or curb weight. According to UBS report, the OEM cost ranges \$300-\$500 for the exhaust system and \$180-\$300 for ECU/sensors (UBS 2017). The average number used as model input for exhaust and ECU also falls into this range.

Table 1. The main ICEV powertrain component costs summary from data sources and this model input (Jegs 2018, A2MAC1 2020, Carparts 2020, Islam, Moawad et al. 2020).

	Engine (\$/kW)	Transmission (\$/kg)	Exhaust (\$)	ECU (\$)
Minimum	9.12	0.32	255	149
Maximum	47.70	1.49	631	715
Average	21.30	1.08	446	235
Model Input	Eq. (4)	1.08	446	235

Similarly, the ICEV powertrain weight is mainly from the components listed above excluding the ECU/sensors. Depending on vehicle types, the engine weights are correlated to vehicle curb weights in the ratio ranging from 0.065 to 0.170 kg/kg , as shown in Fig. 3 (b) (Jegs 2018). The ratios of transmission weight to vehicle curb weight range from 0.038 to 0.121 kg/kg based on multiple A2Mac1 reports (A2MAC1 2020), as shown in Fig. 3 (d). The exhaust system weighs from 10 to 39 kg , which varies little with engine power or curb weight. The default value inputs for engine and transmission weights use the correlations of the dotted lines in Fig. 3 (b) and (c), respectively. An average value of 21 kg is used as the default exhaust system weight. These ICE powertrain components costs/weights were added up and then deducted from the ICEV total to arrive at the equivalent BEV non-powertrain cost/weight.

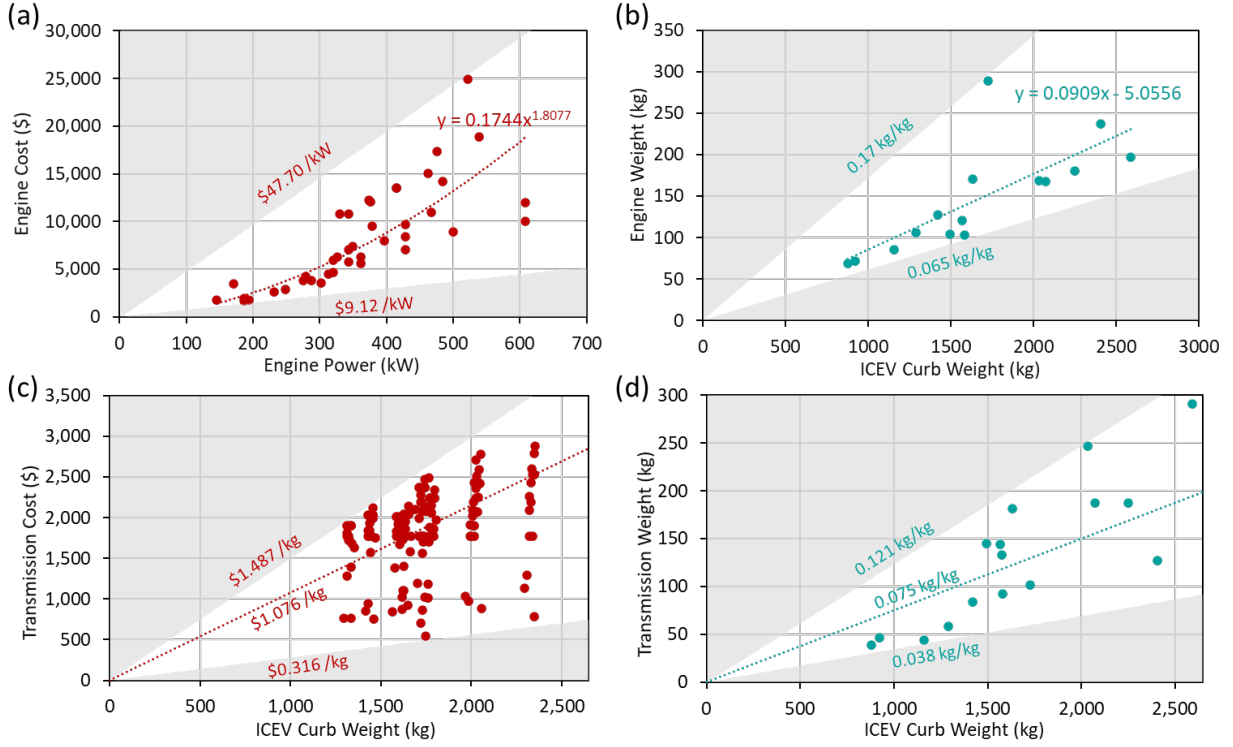


Fig. 3. The internal combustion engine vehicle (a) engine cost and engine power correlation, (b) engine weight and vehicle curb weight correlation, (c) transmission cost and vehicle curb weight correlation, and (d) transmission weight and vehicle curb weight correlation (Jegs 2018, A2MAC1 2020, Carparts 2020, Islam, Moawad et al. 2020). [Data from SI Table S1, S6 and S7]

Two other important vehicle performance parameters, namely fuel efficiency (miles per gallon or MPG) and acceleration time (from 0 to 60 miles per hour), are also used when comparing the consumer favorability between ICEVs and BEVs in Section 3.5. Their values for the ICEV can be formulated in terms of curb weight and engine power as

$$MPG(mi/gal) = 42.45 - 1.53 \times 10^{-2} \times Power(kW) - 7.30 \times 10^{-3} \times Weight(kg) \quad \text{Eq. (5)}$$

$$t_{0-60}^{ICEV}(s) = 1.21 + 96.66 \times Power(kW)^{-0.55} - 0.27 \times Weight(kg)^{-8.60} \quad \text{Eq. (6)}$$

The ICEV acceleration time data are obtained from vehicle websites (Edmunds 2020). The ICEV MPG and acceleration times correlated with vehicle engine powers and curb weights can be viewed in Supplemental

Information (SI) Fig. S1 and S2, respectively. These two parameters were assumed the most attractive features to consumers, which are also easily quantified, as these data are publicly available and are highlighted by most automobile manufacturers on their vehicle webpages. Other parameters, such as top speed and driving range, may also be of importance when comparing favorability between vehicles. However, top speed data were not readily available, and most drivers are content with a top speed of 100 mph, which is within the capabilities of most vehicles. Besides, higher top speeds are of interest only in countries/regions without speed limit or those seeking performance vehicles. Another important parameter, the BEV driving range, is calculated from the energy-mass self-consistent method and discussed by incorporating into the favorability index, which is further elaborated in Section 2.3 and 3.5. The driving range for ICEVs all ranged above 400 miles and, therefore, are not considered as a key criterion; however, the range limitation of BEVs is of great importance and, therefore, this algorithm iterates to converge on the combination of vehicle mass and energy consumption (Watts per mile) to ensure the BEV driving range.

2.2.2 BEV and Electric Powertrain

The electric powertrain comprises an electric motor, an inverter, the on-board charger, battery pack and battery management system (BMS), and other auxiliary components, as demonstrated in Fig. 1. This section models the component-wise electric powertrain weight and OEM cost. Based on data available for BEVs in the U.S. market, the vehicle peak power delivered by electric motor(s) can be represented by a linear correlation, as shown in Fig. 4. It is noteworthy that the power rating of a BEV is significantly higher than that of the corresponding ICEV (compare Fig. 2 and Fig. 4). Meanwhile, there is an intercept shift to the right on the weight axis as well as a slope increase in the linear regression line of the BEV power-weight data as compared to that of ICEVs (Fig. 2). This is mainly due to the additional curb weight of the battery pack. The BEV performance parameters also can be explicitly correlated with curb weight and power.

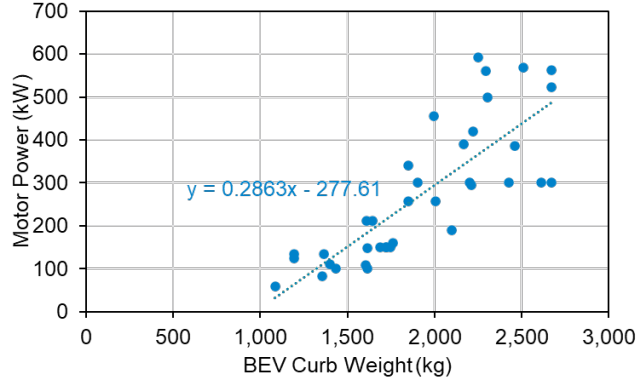


Fig. 4. The motor power-vehicle curb weight correlation and the power-to-weight ratio range of selected market BEV data from official vehicle websites. [Data from SI Table S4]

Unlike ICEV powertrains, reliable information on electric powertrains is limited to a small number of teardown reports on selected BEV models. In this study, the electric powertrain cost and weight modeling are based on 2017 UBS data for the Chevrolet Bolt, 2020 A2Mac1 data for the Tesla Model 3 and Jaguar I-Pace (ADACCESS 2020). The major cost of the electric powertrain is from the battery pack, which leads to the price premium of BEVs over ICEVs. We used the BatPaC 4.0 package to estimate the cost of the battery system including the battery pack (with electrode chemistries of $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$ (NMC622)|graphite) and battery management system (BMS) (Nelson, Ahmed et al. 2019). The total battery system cost (C_{Battery}) correlated with its usable energy (E_{Usable}) is formulated as

$$C_{\text{Battery}}(\$) = -0.0316 \times E_{\text{Usable}}(\text{kWh})^2 + 89.071 \times E_{\text{Usable}}(\text{kWh}) + 3673.5 \quad \text{Eq. (7)}$$

According to BatPaC 4.0 (Nelson, Ahmed et al. 2019), 85% of the total is assumed as the usable energy of the battery pack. Besides the battery, the other components that contribute to the powertrain cost include the high-voltage system, the electric motor, accessories, and the inverter (with boost). The DC/DC converter in the low-voltage system and the on-board charger also contribute to the non-battery cost. All other costs of the components such as the power distribution module, vehicle interface control module, electric vehicle communication controller, cables, and cords are grouped as “E-Auxiliary”, which is assumed equivalent to “ICE Auxiliary” in cost and weight (Fig. 1). Based on UBS teardown report (UBS 2017), the E-Auxiliary

is summed up to \$1207 with negligibly added weight for all vehicle models in this study. The main data sources and parameters input to the model are listed in [Table 2](#). Here the average number of \$3.4/kW from three available sources on inverter cost is used as the input into the model. Given the rapidly decreasing EV manufacturing cost over the year, the UBS data, which is based on a teardown report of the 2017 GM Bolt model, is assumed higher than the OEM cost as of today. Therefore, the 2015 DOE Target number was used for other electric powertrain component costs (*i.e.*, on-board charger and DC/DC converter), which ideally projects the 2020 OEM costs.

Table 2. The main electric powertrain component costs and their data sources.

	Inverter (\$/kW)	Motor (\$/kW)	On-board Charger (\$)	DC/DC Converter (\$)
2020 Tesla Model 3 (ADACCESS 2020)	3.85	-	-	-
2020 Jaguar I-Pace (ADACCESS 2020)	1.70	-	-	-
2017 Chevrolet Bolt (UBS 2017)	4.67	8.00	273	179
2015 DOE Target (Islam, Moawad et al. 2020)	17.00		125	29
Model Input	3.40	8.00	125	29

The electric powertrain weight mainly comes from the battery system and the electric drive unit (motor). The battery weights of different usable energies are also fitted from data generated by BatPaC 4.0 package ([Nelson, Ahmed et al. 2019](#)), which are formulated as

$$Wt_{Battery}(kg) = -0.0006 \times E_{Usable}(kWh)^2 + 4.362 \times E_{Usable}(kWh) + 75.086 \quad \text{Eq. (8)}$$

The motor weights, Wt_{Motor} , based on the best available information ([A2MAC1 2020](#)), can be described in a linear correlation with power

$$Wt_{Motor}(kg) = 42.66 + 0.073 \times Power(kW) \quad \text{Eq. (9)}$$

Similarly, the two BEV performance parameters used in the ICEV/BEV favorability comparison (see Section 3.5) are also modeled. The BEV acceleration times from 0-60 miles per hour has been formulated as

$$t_{0-60}^{BEV}(s) = -4.05 + 0.16 \times Power(kW)^{-5.39} + 62.20 \times Weight(kg)^{-0.35} \quad \text{Eq. (10)}$$

The coefficient values are fitted using official vehicle website public data as shown in SI Fig. S3. The BEV energy efficiency parameter, namely equivalent miles per gallon (MPGe), is estimated later from the calculated battery pack usable energy by the self-consistent method detailed in Section 2.3.

2.2.3 Operating Costs and Others

The annual operating costs (AOCs) of a vehicle are associated with both fixed costs and costs related to the annual distance traveled (ADT). The former includes insurance and registration, while the latter consists of maintenance and repair, energy (gasoline or electricity) consumption, and alternative transportation. Although the ADT of a vehicle is found to be decreasing with the ownership time, according to National Household Travel Survey (NHTS) (NHTS 2017), an approximated average of 12,000 miles per year (NHTS 2017) was used as the default value in the current study. For calculation of energy consumption costs, \$2.5 per gallon (EIA 2021b) and \$0.1 per kWh (EIA 2021a) were assumed for gasoline and electricity prices, respectively. The vehicle registration costs contain an initial one-time fee (i.e., title and plate) and an annual renewal fee, the amount of which varies across the states. A sensitivity analysis on the ADT, the energy price, and the annual discount rate will be presented in the results section. The initial registration cost (RegI) is assumed to be the same for BEVs and ICEVs. For annual registration cost (RegA), an additional annual fee for BEVs is imposed or considered to be added in 2020 in nearly half of the states, to fill the gaps in roadway infrastructure investments derived from gasoline taxes. This additional annual cost for BEVs ranges from \$50 to \$250, with a weighted average of \$78/year based on data sourced from states' Department of Motor Vehicles (DMV) and National Conference of State Legislatures (NCSL 2019).

Vehicle insurance costs mainly depend on vehicle prices. Further simplification was made by assuming a constant annual insurance cost for a given vehicle model even though the insurance rate is expected to decrease annually due to vehicle depreciation and driving records. Fig. S4 shows the effect of the insurance

rate variation on the cost parity calculations. Based on data from The Zebra (Zebra 2020) and quotes on selected vehicle models from major auto insurance companies (Geico 2020, Nationwide 2020, Progressive 2020, StateFarm 2020) as shown in Fig. 5 (a), the annual insurance costs (Ins) of ICEVs and BEVs can be formulated as

$$Ins_{ICEV}(\$) = 0.023 \times VP_{ICEV}(\$) + 682.61 \quad \text{Eq. (11)}$$

$$Ins_{BEV}(\$) = 0.026 \times VP_{BEV}(\$) + 479.71 \quad \text{Eq. (12)}$$

Despite the BEV price premium over ICEV, their regression lines almost overlapped with each other in Fig. 5 (a), indicating the insurance costs of ICEVs and BEVs follow similar trends for their prices. The annual maintenance and repair cost is a function of both the vehicle price (VP) and the annual distance traveled (ADT). Surveyed from public data sources on YourMechanic (YourMechanic 2020) and RepairPal (RepairPal 2020), the annual maintenance and repair costs (MR) of ICEVs and BEVs are formulated by

$$MR_{ICEV}(\$) = [0.0094 \times VP_{ICEV}(\$) + 380.75] \times \frac{ADT(miles)}{12,000} \quad \text{Eq. (13)}$$

$$MR_{BEV}(\$) = [5 \times 10^{-5} \times VP_{BEV}(\$) + 226.04] \times \frac{ADT(miles)}{12,000} \quad \text{Eq. (14)}$$

The available maintenance and repair cost data on BEVs are limited to a small number of light-duty vehicle models. From Fig. 5 (b), it is observed that the ICEV maintenance and repair cost increases with the vehicle price, while the BEV maintenance and repair cost remains steady and low regardless of the vehicle price variance. This is because BEVs are almost maintenance-free with fewer parts to be replaced and no need to regularly change auxiliary fluids (such as engine oil) during the vehicle's life compared with ICEVs. The energy consumption cost during the ownership period is calculated from the energy price, ADT, and vehicle energy efficiency (MPG or MPGe).

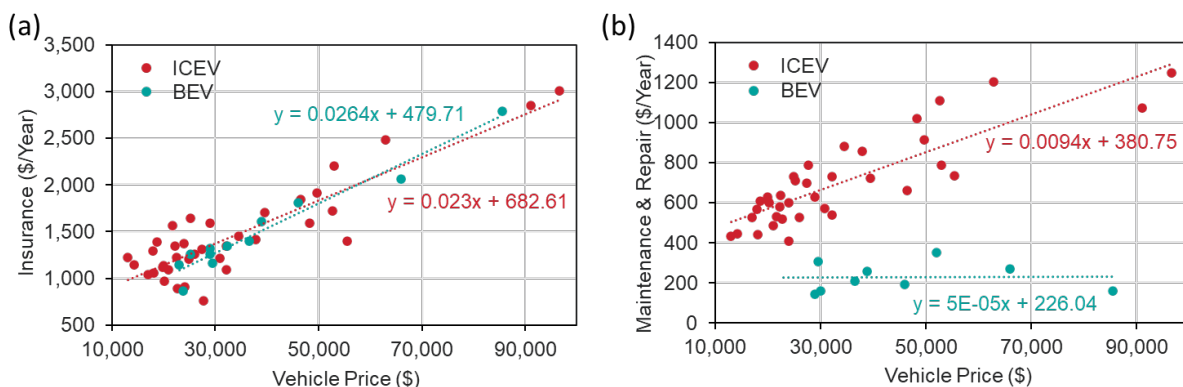


Fig. 5. The vehicle (a) annual insurance costs and (b) annual maintenance and repair cost data, and their correlations with vehicle prices by linear regression. [Data from SI Table S10 and S11]

Home charger (HC) and alternative transportation (AT) are additional costs for BEVs. The home charger installation is a one-time optional cost to enable or upgrade the home charging of BEVs. For a \$0-500 level 1 home charger (NCPEV 2013), it takes a day to fully charge a regular BEV battery, while only several hours are needed for a \$1,200-\$1,800 level 2 home charger (INL 2015, EERE 2019). In this study, we assumed \$700 for the average cost for home charger installation as the default input value. (The cost parity calculation results based on the full TCO with a \$1500 charger is shown in SI Fig. S5.) This study did not consider charger efficiency or charging loss separately and assumes that it can be factored into the price of electricity, which is further discussed in Section 3.4. Note that all “electricity prices” used in this study, if not specified, refer to the “effective electricity prices,” which includes charging losses. Alternative transportation or replacement vehicle cost applies when BEVs do not fulfill the travel needs in driving distance or charging conditions. This cost is affected by the ADT, the BEV driving ranges as well as the energy efficiency of the replacement vehicle. For consistency, BEV replacement miles are assumed made up by an equivalent ICEV, such that the per-mile costs are \$0.63 for a car (1,500 kg or lighter), \$0.66 for a crossover (1,500-2,000 kg), and \$0.97 for an SUV or truck (A2MAC1 2020) (Lutsey and Nicholas 2019). These rates are based on the statistical average costs of separate ICEVs (assumed comparable models with BEVs) in that household, rental or ride-hailing vehicles, and public transportation. Here, a utility factor (UF) is introduced to directly correlate the BEV driving range to the fraction of ADT using the replacement

vehicle. Using the formulation by Bradley et al. (Bradley and Quinn 2010), the utility factor can be written in terms of the DR_{BEV} and DR_{ICEV} in a 6th-order polynomial exponential form of

$$UF = 1 - \exp \left[- \sum_{i=1}^6 C_i \cdot \left(\frac{DR_{BEV}(miles)}{DR_{ICEV}(miles)} \right)^i \right] \quad \text{Eq. (15)}$$

where the coefficients C_1 to C_6 have the values of 10.52, -7.28 , -26.37 , 79.08, -77.36 , and 26.07, respectively, and DR_{ICEV} is set to be 400 miles. The AT is then calculated by multiplying ADT, UF, and the per-mile cost of the replacement vehicles. Note that, although Bradley et al. offer specific utility factors for well-defined ADT ranges, here, a general form of the utility factor is used, to keep consistency with the driving distance sensitivity analysis of different ADT in Section 3.4.

2.3 Self-Consistent Design and Cost Parity

The TCO of ICEVs can be explicitly modeled, component by component, based on the breakdown in section 2.2. For BEVs, however, one of the most important parameters to be determined is the energy storage capacity (kWh) of the battery pack, which in turn determines the vehicle's driving range. Considering that batteries are quite heavy and incur significant costs, the battery's energy capacity has a strong impact on the vehicle's driving range, curb weight, and cost. The vehicle curb weight further affects energy efficiency (MPGe), acceleration, and operating cost. The essential difference between the individual components that relate to the "fuels" of BEVs and ICEVs, is that, while electricity adds no mass, the gasoline tank with fuel adds 10 to 30 kg weight for a 450-mile driving-range ICEV. In turn, the battery pack needed to accommodate the energy for a 200-mile driving range BEV may weigh 275 to 475 kg (18% to 25% of a BEV's curb weight) more and \$7,700 to \$11,600 to the cost. Therefore, we incorporated an energy-mass self-consistent iterative algorithm to represent the impact of the battery pack mass and cost on the vehicle's mass and price in this cost parity study.

As stated in Section 2, two important assumptions to be emphasized for vehicle weight and cost modeling, illustrated in Fig. 1, are: (1) the BEV's non-powertrain cost and mass are assumed equivalent to ICEV of similar model and curb weight; (2) the cost and weight of "ICE Auxiliary" equals "E-Auxiliary", as

elaborated in sections 2.2.2 and 2.2.3. Meanwhile, the BEV energy efficiency, or MPGe, is assumed to vary linearly with vehicle curb weight, with an 85% “battery-to-wheels” efficiency (Gonder, Brooker et al. 2018). Based on these assumptions, the method applied in this BEV-ICEV cost parity study is summarized into a flowchart in Fig. 6, which comprises four parts: ICEV breakdown, BEV design, cost parity period estimation, and break-even price calculation. Specifically, the prices of ICEVs and BEVs are determined by the following steps:

- (1) Select the curb weight (from 1,000 to 2,500 kg) and the engine power for an ICEV. This determines the price of the ICEV.
- (2) Calculate the weight of the engine, transmission, and other components that will not exist in a BEV.
- (3) For the curb weight and a 450-mile driving range, calculate the weight of the fuel tank and the MPG.
- (4) Deduct the masses of these ICEV powertrain components to arrive at the base weight of the vehicle.
- (5) Select the driving range (from 150 to 450 miles) of an equivalent BEV.
- (6) Use the MPGe initial estimate and driving range to calculate the required energy storage capacity of the battery pack.
- (7) Use BatPaC to calculate the mass and cost of the battery pack that is capable of the required power and driving range.
- (8) Add the mass of the battery, motor, inverter, and other BEV powertrain components to the vehicle base weight to arrive at the curb weight of the BEV.
- (9) Calculate the corrected MPGe from the BEV curb weight and update the initial estimate.
- (10) Iterate between steps (6) through (9) until the cost and mass of the battery (and BEV curb weight) converge.

(11) The prices of both the ICEV and the BEV are now known.

The annual operating costs for BEVs and ICEVs are calculated based on their prices determined from this method. The BEV should show a lower annual operating cost. The cost parity studies between equivalent models are conducted in two ways. First, with the assumed annual discount rate, the number of years needed to recoup the extra amount paid for the purchase of the BEV can be calculated from the net present values of the TCO (colored in blue). Second, the maximum allowable BEV price premium over the ICEV can be calculated via the iteration loop (colored in purple) for different cost parity period targets, ranging from 3 to 13 years.

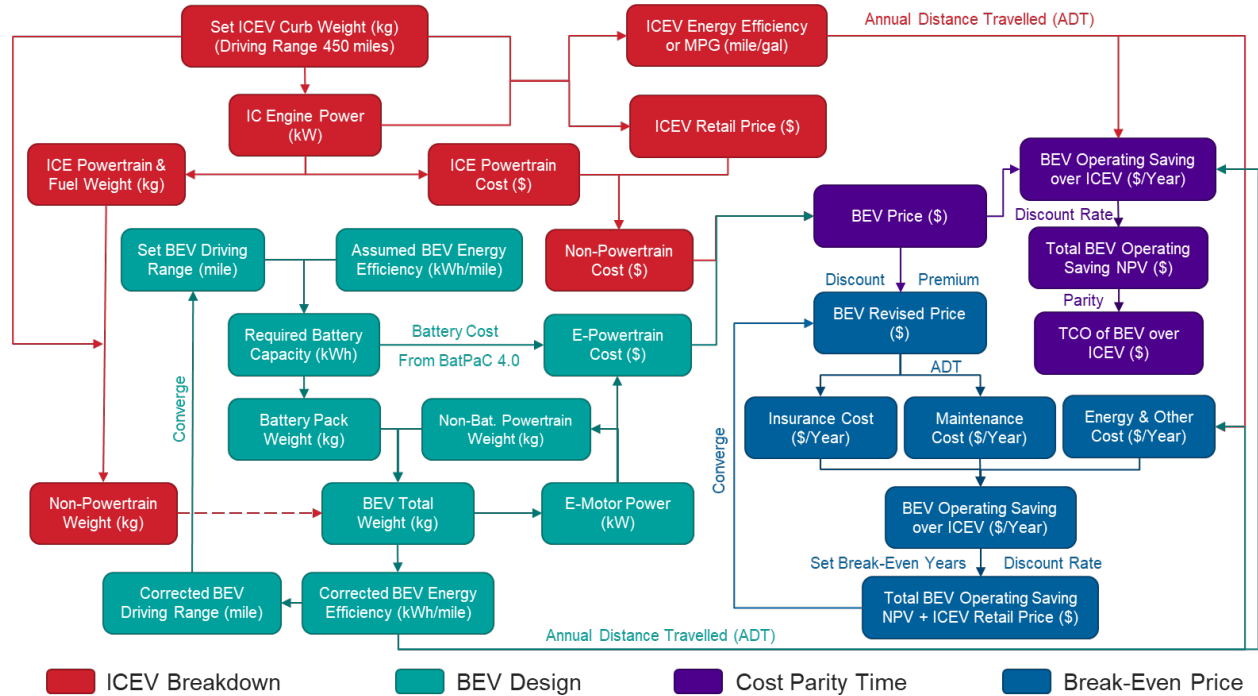


Fig. 6. A method flowchart: the vehicle energy-mass self-consistent design and BEV cost parity study with ICEV.

3. Results and Discussion

This section shows the modeling result of powertrain breakdowns, the operating costs of BEVs, which are then compared with equivalent ICEVs. The cost parity periods of BEVs with equivalent ICEVs are estimated based on TCOs calculated for different vehicle weights (1,000 to 2,500 kg) and BEV driving ranges (150 to 450 miles). The model also calculates the premium that a BEV owner may pay with the expectation of achieving TCO parity within a given ownership period (3-13 years).

The cost parity between BEVs and ICEVs is investigated based on both TCO_{Base} , which reflects the most elementary operation scenario excluding home charger installation and alternative transportation costs, and the full TCO for the extended operation scenario including all costs, as defined in section 2.1. Sensitivity analyses were conducted to study the effects of the annual discount rate, gasoline price, and vehicle ADT on cost parity periods for different BEVs with equivalent ICEVs. Finally, an overall assessment of BEVs (relative to ICEVs) is presented by proposing a “favorability index” for the different vehicle curb weights and driving ranges. A short-form notation for BEVs of different driving ranges is used in the later sections. For example, BEV200 indicates a BEV with an electric driving range of 200 miles.

3.1 Powertrains and Vehicles

Based on the mass and cost assumptions in section 2.3, the differences in curb weight and price between BEVs and equivalent ICEVs are mainly from their powertrains. The converged BEV curb weights, calculated from the energy-mass self-consistent model, are generally heavier than ICEVs of the equivalent models, and longer driving range BEVs tend to weigh more, as shown in Fig. 7 (a). The rare exception is seen for the BEV150 when compared to a corresponding heavy (>1750 kg) vehicle, and is due to the heavier powertrain (Fig. 7 (b)) and a bigger fuel tank of the ICEV. This mass trend in BEVs is caused by the extra weight of batteries. Only BEVs of shorter driving ranges below 200 miles may match ICEVs in curb weights, due to smaller batteries and thus reduced powertrain weights, as demonstrated in Fig. 7 (b). A more straightforward illustration can be viewed from the powertrain weight breakdown in Fig. 7 (c) using a 1,750 kg ICEV vs. an equivalent BEV200 as an example. In the BEV200, the battery pack with BMS takes up to

85% of the total electric powertrain weight, which, together with the 60 kg motor, results in an additional weight of 121 kg over the ICEV powertrain (without fuel tank). However, a BEV450 powertrain can be 440 to 600 kg heavier than the ICEV powertrain, which lowers the MPGe. On the other hand, the BEV prices of all models in this study, i.e., weight 1,000-2,500 kg and range 150-450 miles, are higher than equivalent ICEVs with a price premium ranging from \$4,960 to \$22,500, as shown in Fig. 7 (c), which also results from the high battery pack costs in the electric powertrains (Fig. 7(d)). Again, using the 1,750 kg BEV200 vs. the ICEV powertrain cost breakdown as an example, the battery pack with the BMS takes up to 70% of the total electric powertrain cost (Fig. 7(e)). Taking other major component costs (e.g., the \$1,960 motor and \$833 inverter) into account, the electric powertrain costs \$8,630 more than the ICEV powertrain, as illustrated in Fig. 7 (f). Longer-ranged BEVs cost even more, e.g., BEV450 powertrain can be \$13,800 to \$22,300 more expensive than the ICEV powertrain, as shown in Fig. 7 (d). Compared to a 1,000 kg ICEV with a price of \$20,000, an equivalent BEV450 costs as much as \$34,000 as seen in Fig. 7 (c).

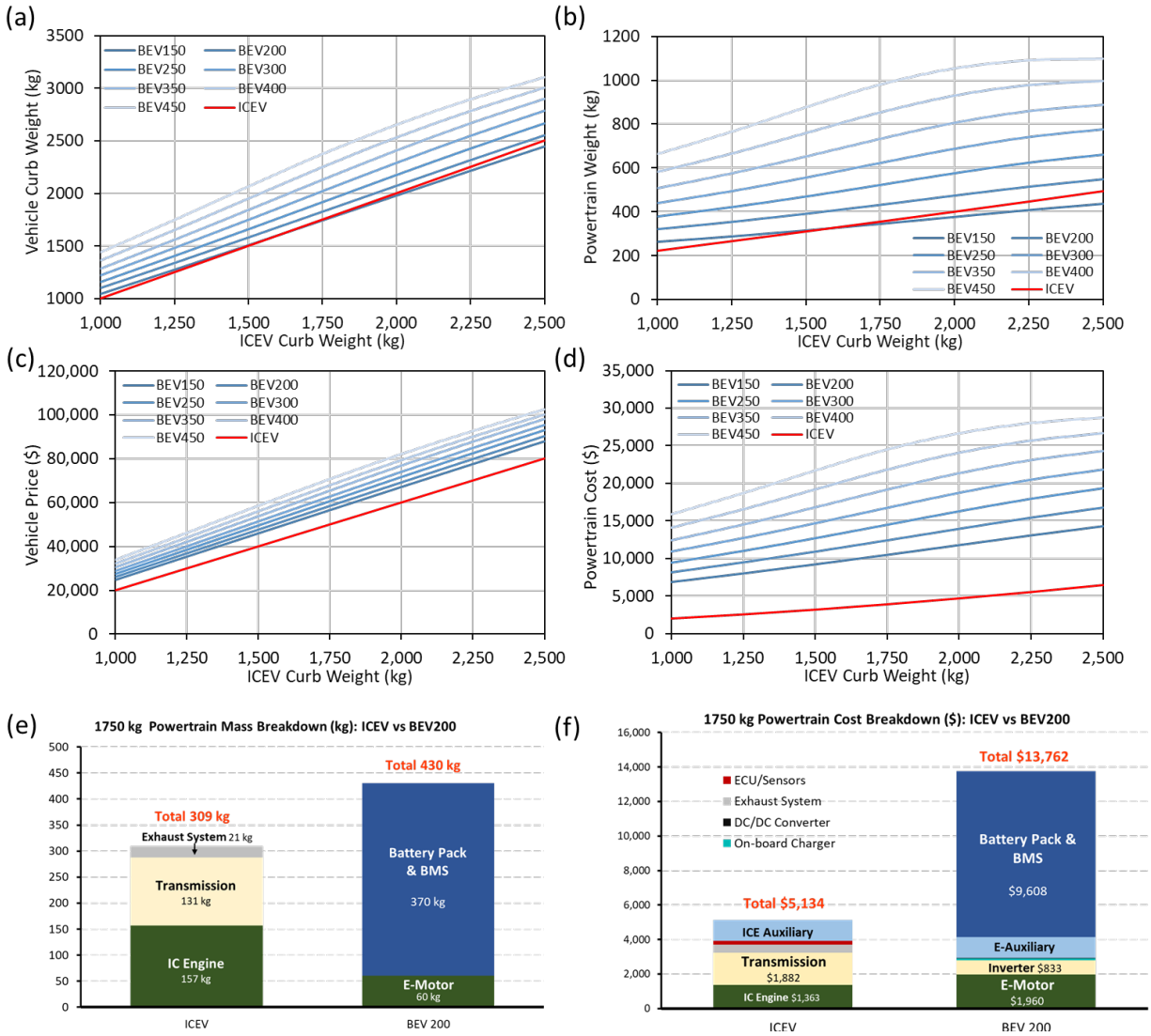


Fig. 7. Calculation results of (a) vehicle curb weights, (b) powertrain total weights, (c) vehicle prices and (d) powertrain total costs for different classes of ICEVs and BEVs, and powertrain (e) weight and (f) cost breakdown by components of 1750 kg ICEV vs BEV200.

3.2 Operating and Performance

Despite the higher price of BEVs, consumers are purchasing these vehicles because of the attractive features such as faster and smoother acceleration, higher pack-to-wheel efficiency, zero emissions at the point of use, and quieter vehicles. Also, the BEV price premium (over the ICEV) can be mitigated and offset during

the ownership period through savings in ownership costs attributable to lower costs of energy and maintenance.

To estimate the annual operating costs (AOCs) of BEVs and ICEVs, it is important to accurately consider their energy efficiencies. In this analysis, gasoline-equivalent miles per gallon or MPGe is employed as the BEV energy efficiency parameter to compare with miles per gallon, or MPG, of the ICEV. The ICEV MPG data are fitted from regression-based on Eq. (5), while the BEV MPGe data are calculated from the usable battery energy and the corresponding BEV driving ranges. As plotted in Fig. 8 (a), the BEV MPGe numbers are several times higher than the ICEV MPG in all curb weight classes. Particularly, the MPGe of BEVs with shorter driving ranges can reach ~150, (e.g., BEV150). By contrast, the MPGe of longer driving range BEVs decreases to below 70 (e.g., BEV450) because of the extra battery mass added for higher usable energy capacity. But this decreased magnitude becomes less as the curb weight increases.

The 0 to 60 miles per hour acceleration time data are also calculated using Eq. (6) and Eq. (10) and using the calculated curb weights data, as presented in Fig. 8 (b). BEVs in general accelerate much faster than ICEVs. Enabled by a high-power battery system, a high-speed motor, and a boost inverter, a BEV can easily achieve high rpm (revolution per minute) and reach 60 mph in about 2.7 s in some cases. This is a desirable feature for many consumers. Lighter BEVs with curb weights under 1,500 kg might accelerate slower than ICEVs, due to one or more factors such as a lower-power electric traction system, or the power limitations of the smaller battery pack.

With the assumed ADT of 12,000 miles/year and gasoline/electricity prices of \$2.5/gal and \$0.1/kWh (which represent minimum expected values), respectively, the operating cost savings of a BEV200 (vs. an equivalent ICEV) with different curb weights are plotted in Fig. 8 (c). The main cost-saving items in the total BEV operating costs (red line) come from energy/fuel (green line) and maintenance/repair (yellow line) costs. The BEV incurs more operating costs (for an ICEV) in insurance (blue line) and alternative transportation (grey line). The vehicle insurance rates, which are typically correlated to the purchase price, are lower for the ICEV.

Overall, for a given driving range, the BEV's annual operating cost-saving (compared to an ICEV with the same curb weight) increases with the vehicle curb weight, as shown in Fig. 8 (d). The figure also shows that for the combination of driving ranges and curb weights presented, the maximum saving is achieved by mid-range BEV250-300. The decreased savings in BEVs of long and short driving ranges are mainly due to the reduced energy efficiency (MPGe) and the increased cost of alternative transportation, respectively. The BEV total operating cost saving ranges from \$316 to \$1,090 per year. This saving margin can be further expanded by hundreds of dollars if/when alternative transportation costs are not incurred.

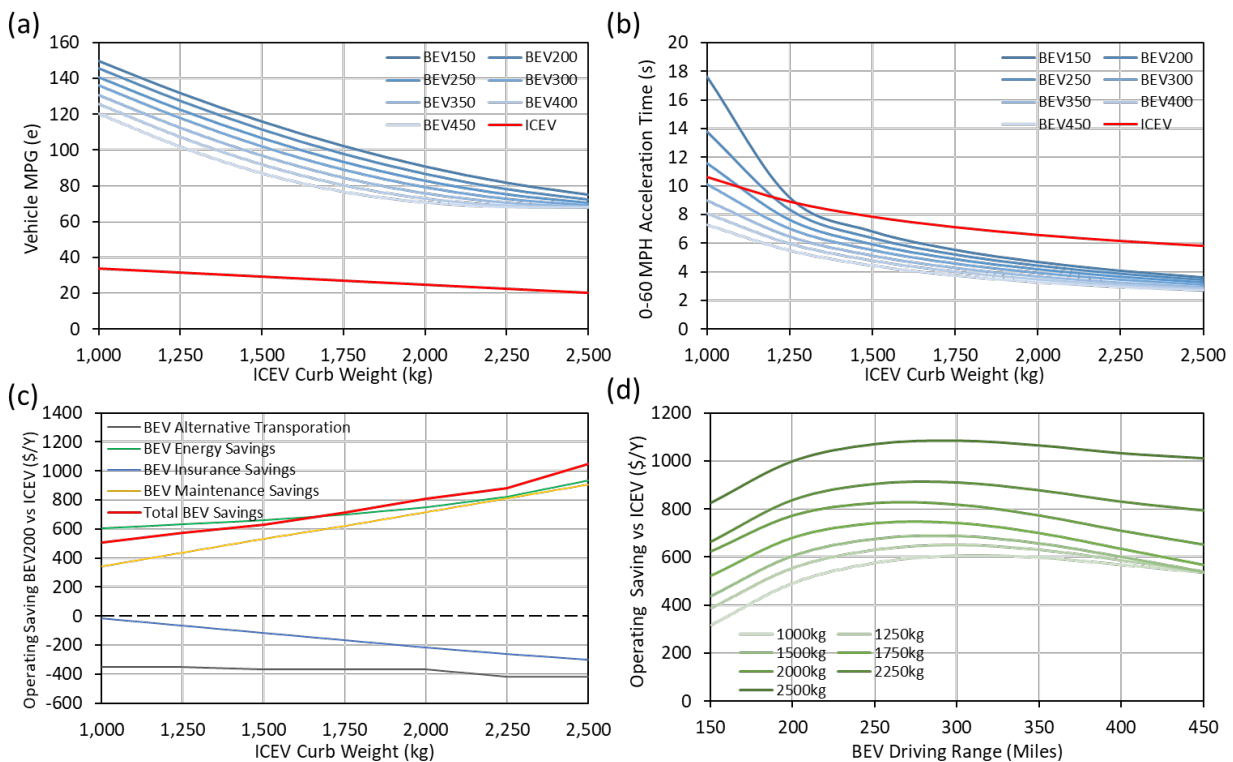


Fig. 8. Calculation results of (a) vehicle energy efficiencies, (b) 0 to 60 mph acceleration times, (c) breakdown of BEV200 operating saving over ICEV, and (d) total BEV operating saving over ICEVs for different curb weights and BEV driving ranges. [Note: The BEV curb weight that corresponds to the ICEV curb weight is shown in Fig. 7(a).]

3.3 Cost Parity

A cost parity analysis is conducted between BEVs and ICEVs of driving ranges from 150 miles to 450 miles and curb weights from 1,000 kg to 2,500 kg, by the method elaborated in section 2.3. The cost parity years for different BEV models can be calculated by matching their TCO with the corresponding ICEV. Due to the variance in different markets, we discuss the scenarios of both TCO_{base} (Fig. 9 (a)) and full TCO (Fig. 9 (b)), where the latter includes the home charger (HC) installation added to the initial cost (IC) of BEV ownership and the alternative transportation cost (AT) added to the annual operating cost (AOC). The comparison shows a notable increase in the BEV cost parity period for the full TCO scenario. Particularly, the ownership of a BEV200 can break even with an ICEV in 6.8-7.7 years without home charger (HC) purchase and extra expenditures for replacement vehicles, but this range increases to 11.2-14.1 years when including both. These prolonged cost parity periods due to extra HC and AT costs, impact the low-curb-weight BEVs more than the heavier ones. It is also seen from Fig. 9 (a) that when the BEV curb weight is less than 1,750 kg the cost parity time increases with increasing curb weight, which is due to the increased BEV price premium over equivalent ICEV (see Fig. 7 (c)). However, for BEV curb weight greater than 1,750 kg, the cost parity time decreases with increasing curb weight, mainly resulting from the higher energy saving from BEV over equivalent ICEV (see Fig. 8 (d)). This trend is more apparent for long-range BEVs. It is notable that the curves for the low driving range vehicles (BEV150 and BEV200 in Fig. 9 (b)) display sharp slope changes and this is because of the step function used to estimate the AT cost, and manifests more prominently in these low range vehicles. More importantly, the short/mid-range BEVs below 200 miles are able to reach cost parity with ICEVs within the average vehicle ownership period of 8 years (Blackley 2019), when excluding the HC and AT costs. With decreasing battery cost over the next decades, this cost parity gap is expected to narrow.

Another way to demonstrate cost parity is through the premium price, which is the allowable price margin added to the BEV to match the same TCO as the ICEV. For example, Fig. 9 (c) shows the BEV200 price premiums calculated from TCO_{base} for different target cost parity periods from 3 to 13 years of ownership.

The curves of different target years indicate that larger price premium margins can be tolerated by heavier BEVs. A BEV200 weighing 2,500 kg has a price premium of \$4,480 and \$19,400 to break even with an ICEV in 3 and 13 years, respectively. In contrast, a BEV200 weighing 1,000 kg has a premium of \$3,010 and \$10,500 for the same time range. This BEV price premium margin goes down when based on a full TCO comparison, as indicated in Fig. 9 (d). The 3- and 13-year break-even price premiums for a 1,000 kg BEV200 become \$1,130 and \$5,650, respectively. These calculated BEV price premiums for different target cost parity periods can also serve as a helpful guide for policymakers as they decide on incentives and tax credits for different BEV models.

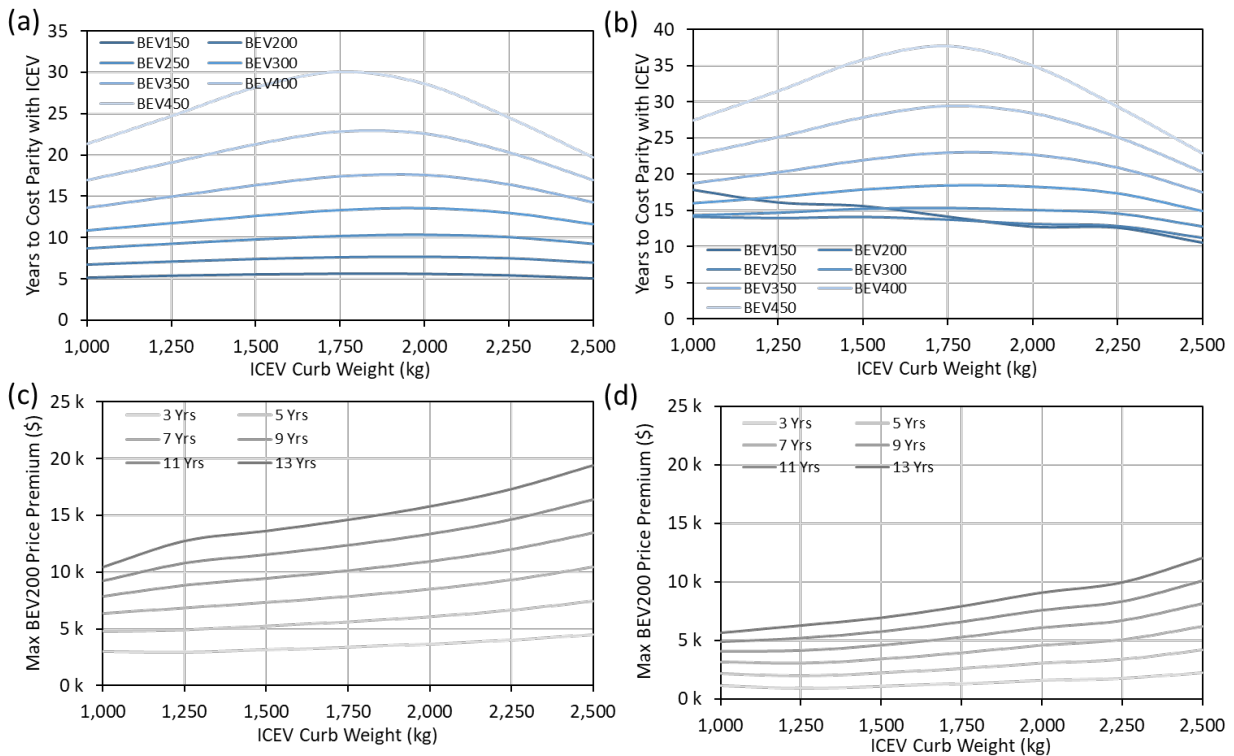


Fig. 9. The cost parity periods for BEVs with ICEVs calculated from (a) TCO_{base} and (b) full TCO, and the allowable BEV price premium margin over ICEVs set for different cost parity periods calculated from (c) TCO_{base} and (d) full TCO for a BEV200. [Note: The BEV curb weight that corresponds to the ICEV curb weight is shown in Fig. 7(a).]

3.4 Impacts from Markets

The sensitivities of the main floating market/society factors affecting vehicle TCO, such as annual discount rate, annual distance traveled, and gasoline/electricity price, are also examined. Their impacts on BEV cost parity with ICEVs are demonstrated via the BEV200 cost parity years plotted for the TCO_{Base} (defined in section 2.1) in Fig. 10 (a), (b), (c), and (d) respectively. The black lines indicate the results using default values for each variable. From the results, the cost parity periods are more sensitive to these variables at mid-high curb weights. Specifically, the increased discount rate postpones the cost parity year. A 10-year cost parity can be met for discount rates lower than 4%, and the years to parity start to increase more rapidly at a given curb weight due to the decreasing time-value of money at discount rates higher than 6%, as shown in Fig. 10 (a). By contrast, increases in ADT and gasoline price both lead to shortened cost parity periods due to more savings in energy consumption. ICEVs with longer travel distance per year also tend to have a higher frequency of maintenance and repair, which contributes to additional operating costs and thus further reduces the cost parity years of BEVs. Tripling the vehicle travel distance from 6,000 to 18,000 miles/year accelerates the cost parity process and shortens the cost parity period from 19.5 to 4.8 years for a 2,000 kg BEV, as shown in Fig. 10 (b). Therefore, vehicle fleets with higher travel loads will benefit earlier and save more by switching to BEVs.

The energy-saving is considered the most important driving force for BEV cost parity with ICEVs. However, the lower gasoline price is one of the key inhibitors against BEV promotion in the U.S. (\$2.5/gal) compared with other main BEV markets such as Europe (\$5/gal or higher) and China (\$3.5/gal or higher) (Petrol 2020). As the fossil fuel resource depletes over the years, gasoline prices in major markets are expected to soar. In the U.S. market, gasoline price is predicted to double to the higher bound of \$5.11/gal in 10 years from now, according to the U.S. Energy Information Administration (EIA) (EIA 2020). The BEV200 cost parity periods for a range of gasoline prices from \$2/gal to \$5/gal are estimated and plotted in Fig. 10 (c). The change in gas price has a significant impact on the cost parity. For instance, the cost parity decreases from 8.4 to 3.5 and 9.7 to 3.9 years for 1,000 and 2,000 kg BEV200, respectively, as gas

price increases from \$2/gal to \$5/gal. The US electricity price varies similarly to gasoline prices between states (EIA 2021a), which is crucial to the economic advantageousness of a powertrain. Fig. 10 (d) shows the impact of electricity prices, ranging from \$0.05/kWh to \$0.3/kWh, on cost parity periods between BEV200 and ICEV. Tripled electricity price results in up to five times longer cost parity time.

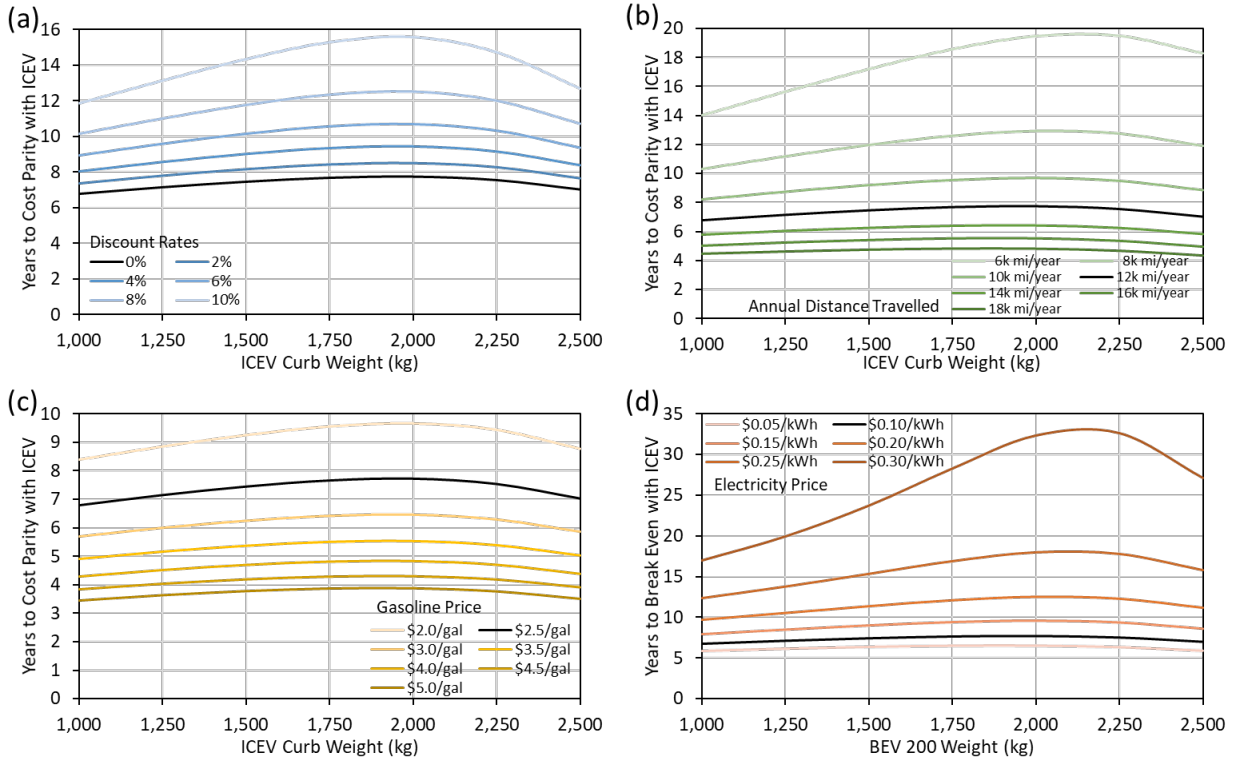


Fig. 10. Impacts of (a) annual discount rate, (b) annual distance traveled, (c) gasoline price and (d) electricity price on BEV200 cost parity periods with ICEV calculated based on TCO_{base} . Black line indicates baseline values. [Note: The BEV curb weight that corresponds to the ICEV curb weight is shown in Fig. 7(a).]

The results in Fig. 10 (d) also provide insight into the effect of charging efficiency on the cost parity period. For instance, the process of charging involves some energy loss (heat generation, cooling requirement). These losses are considered negligible in the baseline case since it is assumed charging is done overnight, at home, where low charging currents can be used (charging losses are directly proportional to current). However, in some situations (e.g., fast charging at a rest stop) the losses can be considerable, and the net

effect is that more electric energy is drawn. This can be factored in by considering a correspondingly higher electricity rate. For example, a 16% energy loss (Apostolaki-Iosifidou, Codani et al. 2017) during charging can be represented with a ~19% higher rate in the effective electricity price, *i.e.* using a rate of \$0.119/kWh for the analysis (instead of the \$0.10/kWh baseline number) would increase the cost parity period for a 1750 kg BEV200 from 7.7 to 8.2 years, or ~7%.

Finally, note that the baseline gasoline/electricity prices of \$2.5/gal and \$0.1/kWh, respectively, represent minimum expected values in the U.S, yielding “best-case” scenarios for both vehicle types. Recalculating the cost parity using \$3.0/gal and \$0.15/kWh to represent current, average U.S prices (EIA 2021a, EIA 2021b) shows a similar trend and a slightly longer time in the cost parity years (compare Figures S7 to 9a). Figure 11 shows that the cost parity results are relatively invariant if both prices are on similar ends of the cost spectrum. For instance, price combinations of \$2.5/gal and \$0.1/kWh (low); \$3.5/gal and \$0.2/kWh (medium); and \$4.5/gal and \$0.3/kWh (high) all result in 7.4 ± 0.3 years to cost parity for a 1,750 kg BEV200 according to the figure. Deviations in cost parity from the baseline case (\$2.5/gal and \$0.1/kWh) are greatest when the gasoline price remains low and the electricity prices rise. Figure 11 also provides years to cost parity for average gasoline/electricity prices in each state in 2020 to show how location within the U.S. can impact results. The years to cost parity range from ~5 in Washington state to ~10 years in Hawaii, while most states cluster around 6 to 8 years.

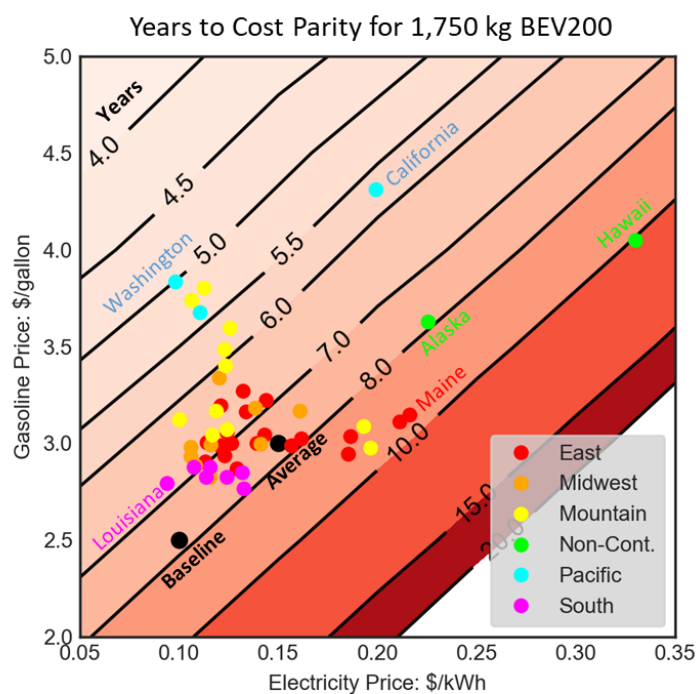


Fig. 11. A contour plot of cost parity years for different gasoline and electricity prices based on a 1,750 kg BEV200 with equivalent ICEVs calculated from TCO_{base} . The contour lines represent constant cost parity in years. The colored data points are the years to cost parity for different US states based on EIA data for the gasoline prices as of July 13, 2021 and the average electricity prices over the year 2020 (EIA 2021a, EIA 2021b). The “Baseline” data point is the baseline of this study, and the “Average” data point is used to generate Fig. S7. (For data, see Table S12)

3.5 BEV Favorability

Thus far, it has been shown that the BEVs weigh and cost more, mainly because of the battery. However, the annual cost of ownership of the BEV is lower because of the cheaper price of electric energy per mile and nearly maintenance-free operations. The net effect is that short-range BEVs with smaller batteries can achieve parity with ICEVs in as low as 5.1 years on cost of ownership basis. The electric powertrain also offers the added attraction of rapid acceleration. Moreover, the high “energy-to-wheels” efficiency and

zero-emission driving experience make BEVs a more environmentally friendly and sustainable choice for the future. Here, the zero-emission refers to driving only and not to the production of the vehicle or the generation of electricity. Although more categorized assessments from customer-oriented and society-oriented perspectives are suggested by some studies (Letmathe and Soares 2017), the boundary between the two is obscure. Because many societal costs have been further passed on to customers and manufacturers, such as the additional tax imposed on fuel prices and the Corporate Average Fuel Economy (CAFE) standard due to greenhouse gas emissions. Therefore, by factoring all these considerations into a consolidated index, we define a comprehensive Favorability Index (FI) for BEVs as

$$FI = \frac{\frac{DR_{BEV}(miles)}{DR_{ICEV}(miles)}}{\frac{t_{0-60}^{BEV}(s)}{t_{0-60}^{ICEV}(s)} \times \frac{GHG_{BEV}(MT\ CO_2Eq.)}{GHG_{ICEV}(MT\ CO_2Eq.)}} \cdot \frac{AYO(years)}{YTCP(years)} \quad \text{Eq. (16)}$$

where the GHG_{BEV} and GHG_{ICEV} are the metric tons per year of greenhouse gas (CO_2) equivalent (EPA 2020) for the BEV and ICEV, respectively (data from SI Fig. S6). The $YTCP$ is the years to cost parity based on TCO_{base} , (data from Fig. 9 (a)), and the AYO is the vehicle average years of ownership that is assumed to be 8 years in this evaluation based on latest statistics (Blackley 2019). The values for acceleration (t_{0-60}) come from the data in Fig. 8 (b), and the ICEV driving range (DR_{ICEV}) is kept constant at 450 miles. According to this definition, an index greater than unity indicates that the BEV is preferable. Generally, the FI results plotted in Fig. 12 (a) show that shorter-ranged and heavier BEVs are more favorable. If taking one as an index reference, BEVs are seen to be more favorable than ICEVs starting at 2,250 kg curb weights, while all BEV models become favorable from 2,500 kg curb weights or heavier. The improving favorability of heavier vehicles with shorter driving ranges can be traced to their contributing factors (ratios), as shown in Fig. 12 (b) and (c). Though the limited driving range of BEVs is somewhat discouraging, they produce much less greenhouse gas emissions for all models and offer faster acceleration for most 1,250 kg or heavier curb-weight models. Besides, most BEVs of 200 miles or less in driving ranges can reach cost parity with ICEVs under the average U.S. vehicle ownership period of 8 years

without incentives or subsidies. Substantial reduction in the cost of the battery, which may occur in the future, would reduce the number of years to cost parity (YTCP) for all BEVs, and thus increase their Favorability Index (FI). The favorability index defined above is merely a consolidation of some of the factors considered in this paper and serves only as a guiding parameter. For simplicity, the ratios are represented on the basis of direct or inverse proportionality, with linear contributions, and without applying weights. Needless to say, the favorability of a vehicle depends on the perspective (individual consumer, organization, regulator, etc.) and may consider these and other features, some of which may be harder to quantify (e.g., recharging vs. refueling, etc.) and are beyond the scope of this paper.

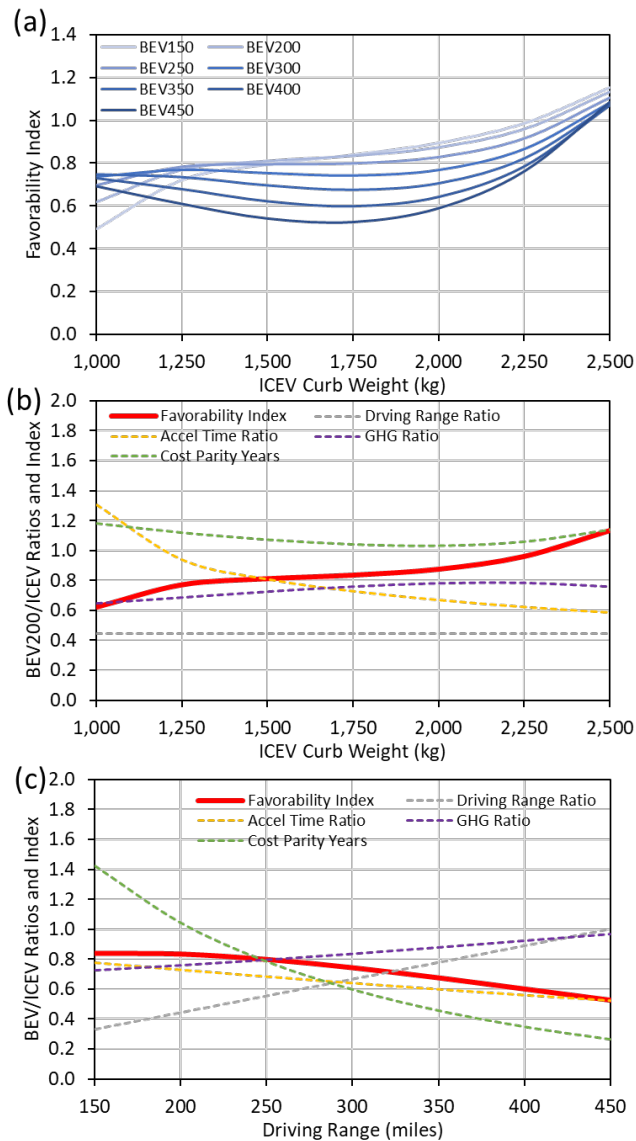


Fig. 12. (a) The BEV favorability indices of driving ranges from 150 to 450 miles and curb weights from 1,000 to 2,500 kg, and the breakdown of the indices for (b) BEV200s of different curb weights and (c) 1,750 kg class BEVs of different driving ranges. [Note: The BEV curb weight that corresponds to the ICEV curb weight is shown in Fig. 7(a).]

4. Conclusion and Policy Implications

The BEV is regarded as an important part of future transportation electrification as a substitute for ICE vehicles. Despite the existing purchase price premium from high battery cost, BEVs are shown to be competitive with ICEVs and can be expected to be more prevalent in the market due to several attractive features, such as higher energy efficiency, lower maintenance frequency, faster acceleration, and noiseless and emission-free operation. Based on the total cost of ownership calculations, this study showed that today's mass-produced BEVs in the U.S. market can potentially reach cost parity with ICEVs from energy and maintenance savings, in a period much shorter than the average vehicle ownership for selected models. Specifically, heavier BEVs with shorter driving ranges will recoup the initial price premium faster relative to equivalent ICEVs. It is also found that the optional expense on home charger installation and alternative transportation adds to the cost parity period. Without these two costs, a BEV200 can reach cost parity with an ICEV in 6.8 and 7.7 years for 1,000 and 2,500 kg ICEV curb weight vehicles, respectively, whereas this period becomes 11.2 and 14.1 years when including both costs. Higher gasoline prices/lower electricity prices, longer annual distance traveled, and a lower discount rate all lead to shortened cost parity periods. Lastly, an overall evaluation of the competitiveness of BEVs with equivalent ICEVs from both societal and environmental impacts was conducted by factoring all contributing parameters into an as-defined BEV favorability index. Though purchase price premium and limited driving range are still the main challenges to be overcome in the next decade of BEV development, today's BEVs of short driving ranges and heavier curb weights turn out to be more favorable than equivalent ICEVs from this comprehensive index. Note that all vehicle operating costs in this study are based on averaged numbers across US, despite their location-

wise variances, *e.g.*, gas/electricity prices, insurance rates. Therefore, the place of residence has an impact on the economic advantageousness of the decision for different powertrains. It should also be noted that this study does not incorporate positive impacts from BEV incentives or subsidies, as well as other policy-induced, yet unquantifiable, savings such as high-occupancy vehicle (HOV) lane access for BEVs in some U.S. states (Tal and Nicholas 2014), which would result in a further inclined favorability towards BEVs.

Due to increased environmental concerns, many governments in Europe and Asia, as well as some U.S. states (e.g. California), have mandated the elimination of new ICEVs by certain dates (Burch and Gilchrist 2018, Fulton, Jaffe et al. 2019). The rationale is to transition over to renewable electricity and reduce the emission of greenhouse gas. These goals can be met with the growth of renewable energy generation, the ability to buffer their supply and demand cycles with energy storage, the availability of a vehicle charging infrastructure, and the availability of low-cost electric vehicles. The cost of the vehicles will continue to have a major impact on the market penetration of electric vehicles.

The current higher purchase price of the BEV, relative to an equivalent ICEV, is the first hurdle for the consumer. This price difference is primarily due to the high cost of the battery. R&D investments in battery technology can lead to improved energy densities and lower costs. Despite the higher purchase expense, some discerning buyers and especially those that can afford the higher purchase price are buying the EVs and, therefore, are able to realize the lower ownership cost. Fig. 9 showed that the vehicles with a shorter driving range can reach ownership cost parity in as little as 5 years, which will become even shorter as battery technology innovation and BEV market expansion continues. Policies favoring the market penetration of these vehicles will help reduce the costs of electric powertrain components such as the battery, electric motor, etc., through the rules of economies of scale. The growth of the charging infrastructure and fast charging technologies will mitigate the oft-quoted range anxiety of potential buyers.

Market trends indicate a preference for heavy vehicles such as SUVs and pick-up trucks. The results presented here (SI Fig. S6) showed that the heavier ICEVs generate the most greenhouse gas. Greenhouse gas emissions will be more effectively lowered if these heavy ICEVs can be replaced with BEVs. Also, the

heavier BEVs are better economic substitutes of equivalent ICEVs due to greater savings in operating cost (Fig. 8), leading to a shorter cost-parity period (Fig. 9). On the other hand, these heavier BEVs require larger and more expensive batteries, especially if a longer driving range is desired. Fast and frequent charging can lessen the energy storage load (i.e., smaller, cheaper battery) and will be possible with the growth of the recharging infrastructure. Incentives to offset the burden of frequent charging would facilitate the replacement of these heavier vehicles from combustion engines to electric drive.

The results presented in this study indicate that the longer-range vehicles pose more of a challenge for cost parity because of their need for a bigger and more costly battery. Economic and other incentives, such as parking closer to buildings, access to HOV lanes, expanded (fast) charging infrastructure, etc. will help the transition from ICEVs. Cost reductions of the battery will follow as a result of economies of scale. However, not all heavy vehicles need a long driving range and therefore can get by with a smaller battery. Electric buses that recharge after one or more loops are an option to reduce the carbon footprint.

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