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Article

Battery Sizing for Plug-in Hybrid Electric Vehicles in Beijing: A TCO Model Based Analysis

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Abstract: This paper proposes a total cost of ownership (TCO) model for battery sizing of plug-in hybrid electric vehicles (PHEVs). The proposed systematic TCO model innovatively integrates the Beijing driving database and optimal PHEV energy management strategies developed earlier. The TCO, including battery, fuel, electricity, and salvage costs, is calculated in yearly cash flows. The salvage cost, based on battery degradation model, is proposed for the first time. The results show that the optimal battery size for PHEVs in Beijing is 6–8 kWh. Several additional scenarios are also analyzed: (1) 10% increase in battery price or discount rate leads to an optimal battery size of 6 kWh, and 10% increase in fuel price shifts the optimal battery size to 8 kWh; (2) the longer and more dispersive daily range distribution in the U.S. increases the optimal battery size to 14 kWh; (3) the subsidy in China results in an optimal battery size of 13 kWh, while that in the U.S. results in 17 kWh, and a fuel savings rate based subsidy policy is innovatively proposed; (4) the optimal battery size with $Li_4Ti_5O_{12}$ batteries is 2 kWh, but the TCO of $Li_4Ti_5O_{12}$ batteries is higher than that of $LiFePO_4$ batteries.

Keywords: battery sizing; total cost of ownership; plug-in hybrid electric vehicle

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are very popular these days. They have the advantages of both battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs) [1]. When the battery is charged through grid electricity, the PHEV operates like a BEV with high powertrain efficiency and no emissions. When the battery is discharged, the PHEV operates like an HEV without the anxiety of electric range. Although this new configuration introduces many advantages, it also brings challenges. Battery sizing is one of the main challenges [2,3]. If the onboard battery is too large, the high cost of the battery will hinder the promotion of PHEVs. On the other hand, if the onboard battery is too small, the fuel savings benefit will not attract enough customers. This paper aims to establish a method to determine the optimal battery size for PHEVs.

To optimize battery size, the total cost of ownership (TCO) model is introduced to evaluate the total cost from the perspective of a vehicle user. There are generally three methods of utilizing the TCO model. The first method is called direct optimization, in which the analytical result of the optimal battery is given. Lin describes a typical example of direct optimization, wherein the consumer cost is represented as a function of the electric range of PHEVs [4]. All components of the consumer cost were also written as functions of the electric range by making numerous simplifications and assumptions. Finally, by making the optimization problem convex, the analytical optimal result was obtained. Further, Murgovski combined the battery sizing problem with the energy management problem. Battery cost was normalized by distance and the optimization problem was finally solved by convex programming [5]. The second method is the illustration of payback period compared with conventional vehicles (CVs). Raghavan analyzed the payback period of a PHEV relative to both HEV and CV [6]. Ernst found that the amortization time for PHEVs with 4 kWh batteries is about 6 years if charged daily, considering a battery price of €1000/kWh; if the battery price is reduced by half, the amortization time will be shortened to 3 years [7]. Al-Alawi and Bradley indicated in their study that there is little consensus on the payback period of PHEVs relative to CVs because of the high sensitivity of TCOs to the assumptions implicit in each model [8]. They reviewed four major TCO models and compared them with harmonized parameters [9,10]. The third method is through comparison of TCOs, wherein the configuration with the minimum TCO corresponds to the optimal one. Al-Alawi and Bradley established a very detailed TCO model which takes various costs into account, such as maintenance fee and registration renewal cost [8]. This results in the highest TCO of $0.28/km for CV and $0.27/km for PHEV20 in previous studies. Before Al-Alawi's model, the highest TCO came from the research by Markel and Simpson [11], with TCO for CV of $0.22/km and TCO for PHEV20 of $0.23/km.

The establishment of the TCO model is the most important step no matter how it is utilized. Though many uncommon sub-costs could be included in the TCO model, such as the refueling hassle [4], the TCO model usually has three basic components: purchase cost, yearly usage cost, and salvage cost. Purchase cost usually refers to the combined costs of the glider and the powertrain components. In the study by Markel and Simpson [11], the estimated glider cost was constant $17,390 excluding the cost of the powertrain, which was expressed as a linear function of the rated power. Al-Alawi and Bradley emphasized on the comparison between PHEVs and CVs [8]. Thus, only the incremental cost of PHEVs, mainly from the batteries, is considered. The battery cost model is usually expressed as the product of battery energy and battery cost per unit energy [12]. For the cost of usage, more and more studies have begun to realize that the usage cost of PHEVs is closely related to the daily driving range distribution [5]. Nevertheless, the utility factor weighted fuel consumption method has not been used until recently [8]. Salvage cost is considered to be the difference between original cost and degradation cost. The degradation cost is expressed as battery capital cost divided by lifetime output energy (or capacity) [13,14].

According to the research review, it is evident that the TCO of PHEVs varies from region to region because of variations in the energy prices and driving patterns. Thus, the optimal battery size should also vary from region to region. Unfortunately, only research papers on the U.S. [4,8,11] and Europe [7] are available, and no such research on China could be found. Based on this status, this study intends to propose a TCO model to analyze the PHEV battery size in Beijing on the basis of the daily driving distance database of Beijing, the real Chinese battery test results, and the Chinese economic parameters.

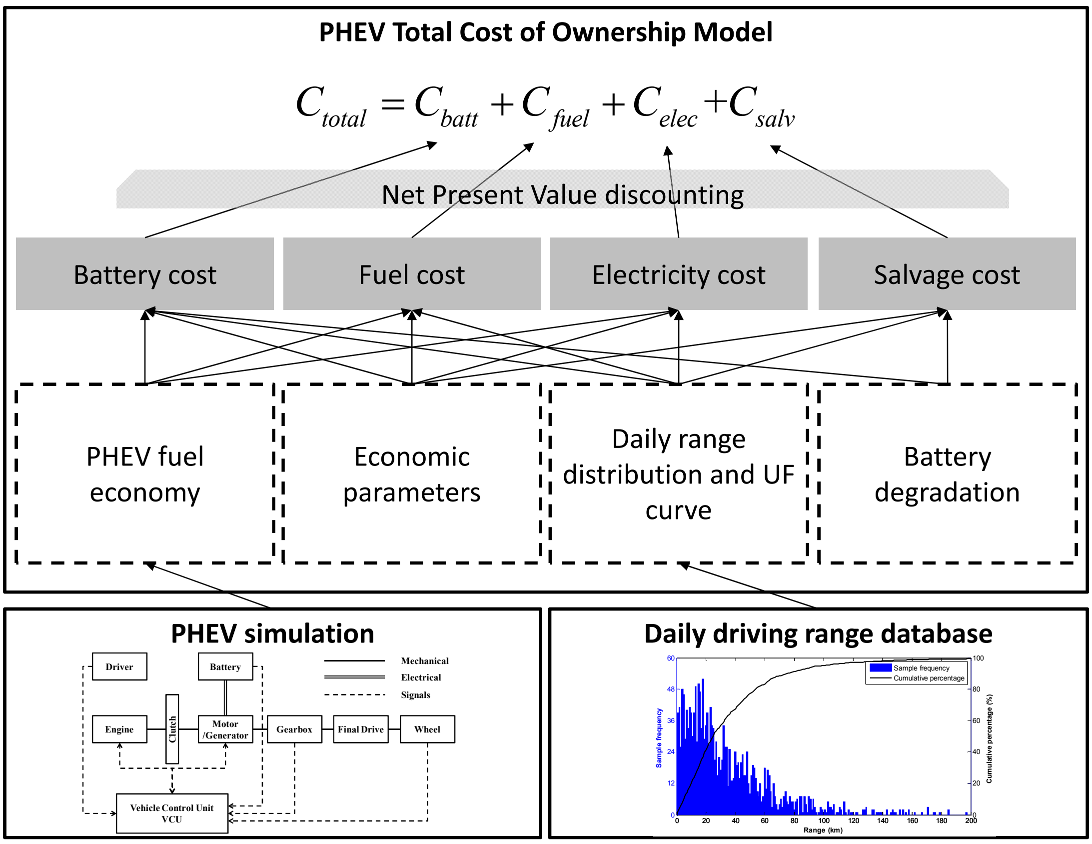
The remaining paper can be divided into the following sections: the details of the TCO model are introduced in Section 2; the result of the baseline scenario is presented in Section 3; in Section 4, the scenario analyses are illustrated, including the sensitivity analysis, a comparative study of data from Beijing and U.S., the subsidy policy analysis, and a comparison between $LiFePO_4$ and $Li_4Ti_5O_{12}$ batteries.

2. The TCO Model

2.1. Model Overview

Aiming to optimize the battery size for PHEVs in Beijing, the TCO model takes into account four sub-costs, including battery, fuel, electricity, and salvage costs, as shown in Figure 1.

Figure 1. The TCO model illustration.

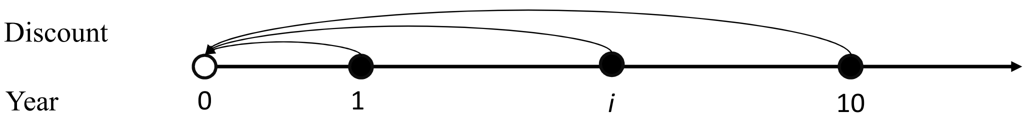


Other powertrain components including the engine and the motor are considered to be invariant with respect to battery capacity [6]. Additional costs, such as insurance and maintenance costs, have not been proved to be closely related to the battery size and are thus not included in the model [10].

All costs are calculated year by year. In other words, the costs are presented in the form of yearly cash flows. As it is an economic analysis, the net present value (NPV) is employed to deal with cash flows of the future. In the NPV calculation, each cash flow in the future is discounted to its net present value, as depicted by arrows in Figure 2. Total cash flow in each year $C_{\text{total}}(i)$ is always equal to the summation of the four sub-costs viz. battery, fuel, electricity, and salvage costs. The NPV value of the TCO is the sum of the product of the yearly cash flows and the corresponding discount rate shown as Figure 2.

Figure 2. The cash flows and matrix.

$$T = \left[\frac{1}{(1+t)^0} \quad \frac{1}{(1+t)^1} \quad \cdots \quad \frac{1}{(1+t)^i} \quad \cdots \quad \frac{1}{(1+t)^N} \right]^T$$



$$\begin{bmatrix} C_{batt} \\ C_{fuel} \\ C_{elec} \\ C_{salv} \end{bmatrix} = \begin{bmatrix} C_{batt}(0) & C_{batt}(1) & \cdots & C_{batt}(i) & \cdots & C_{batt}(N) \\ C_{fuel}(0) & C_{fuel}(1) & \cdots & C_{fuel}(i) & \cdots & C_{fuel}(N) \\ C_{elec}(0) & C_{elec}(1) & \cdots & C_{elec}(i) & \cdots & C_{elec}(N) \\ C_{salv}(0) & C_{salv}(1) & \cdots & C_{salv}(i) & \cdots & C_{salv}(N) \end{bmatrix} \times T$$

$$C_{total} = \left[C_{total}(0) \quad C_{total}(1) \quad \cdots \quad C_{total}(i) \quad \cdots \quad C_{total}(N) \right] \times T$$

Sub-cost calculation is conducted based on four sub-settings, shown in Figure 1. The PHEV fuel economy part includes the fuel consumption and electricity consumption test results in both charge depleting (CD) and charge sustaining (CS) stages, which are inputs from the supportive PHEV simulation models. The economic parameters part includes settings of the fuel price, battery price, discount rate, and so on. The daily range distribution is first derived from the supportive daily driving range database and is then converted to the UF curve. The battery degradation part includes the results of the battery degradation tests.

The vehicle studied in this paper is a typical parallel hybrid compact sedan, the simulation model of which will be introduced later in Section 2.6. The daily driving range distribution is derived from the daily driving range database of Beijing, which will be explained later in Section 2.7. The PHEV simulation model and the daily driving range database are regarded as two additional models supporting the TCO calculation. Should other simulation tools or databases be preferred, they can also be connected to the TCO model proposed in this paper.

2.2. Battery Cost

The battery cost is linearly dependent on battery price, as it is the most widely used model in previous studies [12,14]. Suppose the battery price is P_{batt} RMB/kWh, the battery has an energy of

e kWh, and the battery purchase cost is $P_{\text{batt}} \cdot e$ RMB and the annual discount rate is t. Because all costs are in the form of cash flows, the battery cost appears every year during the evaluation period. As a result, $z_{\text{on}}(i)$, the battery install decision at year i is added to the model. The decision is made based on the following three rules: (1) at year 0, when the user purchases the vehicle, he purchases the battery as well, $z_{\text{on}}(0) = 1$; (2) during the evaluation period, if the relative capacity of the battery drops below 0.8 because of degradation in year i (13), the battery replacement takes place at the end of year i. The degradation model will be discussed later in Section 2.5; (3) for the last year in the evaluation period, no battery replacement takes place, $z_{\text{on}}(\text{N}) = 0$. The battery costs during the evaluation period are finally multiplied with the discount rate as shown in Equation (1) below:

$$C_{\text{batt}} = \sum_{i=0}^{N} \frac{P_{\text{batt}} \cdot e_{\text{batt}} \cdot z_{\text{on}}(i)}{(1+t)^i} \tag{1}$$

2.3. Fuel Cost

The fuel cost is calculated using the utility factor weighting method suggested in SAE J2841 [14]. The utility factor is used to describe the utility of the charge depleting mode of the PHEV in daily life. The higher the utility factor is, the more the charge depleting mode is utilized in daily life. It is derived from the daily driving range data. For detailed information on utility factors, please refer to the SAE J2841 standard. However in this paper, the fuel economy results and utility factor curve are replaced with the simulated fuel consumptions and the real utility factor curve of Beijing, respectively.

The utility factor curve in this study is derived from the research on the daily driving distance of Beijing passenger vehicles [15]. The daily driving range distribution is fitted with a Gamma distribution as suggested by Lin [16]. Then, the distribution function is converted to the utility factor based on the conversion equation derived by the author [17].

The fuel economy results are obtained from the additional model of PHEV simulation. The CD and CS fuel consumptions of a PHEV with a battery energy of e kWh are denoted by $\text{FC}_{\text{CD}}(e)$ and $\text{FC}_{\text{CS}}(e)$, respectively, and the charge depletion range is denoted by $R_{\text{CD}}(e)$. Besides the utility factor, the above three indices are the most significant parameters determining the fuel economy of PHEVs. Yearly cost is assumed to be the daily average fuel cost multiplied by the number of driving days.

Finally, if the fuel price is denoted by P_{fuel}, the average daily driving range is denoted by R_{avg}, the corresponding utility factor is denoted by $\text{UF}(R_{\text{CD}})$, the driving days is denoted by d_{drv} and the vehicle's driving pattern remains the same during the evaluation period, the total fuel cost can be expressed as given in Equation (2). It should also be noticed that the fuel cost is not counted until the end of each year; so the summation starts at the end of the 1st year:

$$C_{\text{fuel}} = \text{AFC} \cdot R_{\text{avg}} \cdot d_{\text{drv}} \cdot P_{\text{fuel}} / 100 \cdot \sum_{i=1}^{N} \frac{1}{(1+t)^i} \tag{2}$$

Average fuel consumption (AFC) is provided as Equation (3) for convenience:

$$\text{AFC} = \text{FC}_{\text{CD}} \cdot \text{UF}(R_{\text{CD}}) + \text{FC}_{\text{CS}} \cdot (1 - \text{UF}(R_{\text{CD}})) \tag{3}$$

2.4. Electricity Cost

The electricity cost is very similar to the fuel cost with the only difference being in the electricity consumption in the CS stage. According to SAE J2841 [18], the tested electricity consumption during the test should be converted to the equivalent fuel consumption. This procedure is known as SOC correction [19]. Thus, no electricity is consumed in the CS stage. Finally, if the electricity price is denoted by P_{elec}, the average daily driving range is denoted by R_{avg}, the electricity consumption in CD stage is denoted by EC_{CD}, the driving days in a year is denoted by d_{drv} and the vehicle's driving pattern remains the same during the evaluation period, then, the total electricity cost in the evaluation period is expressed as Equation (4):

$$C_{\text{elec}} = \text{AEC} \cdot R_{\text{avg}} \cdot d_{\text{drv}} \cdot P_{\text{elec}} / 100 \cdot \sum_{i=1}^{N} \frac{1}{(1+t)^{i}} \tag{4}$$

The average electricity consumption (AEC) is provided as Equation (5) for convenience:

$$\text{AEC} = \text{EC}_{\text{CD}} \cdot \text{UF}(R_{\text{CD}}) \tag{5}$$

2.5. Salvage Cost

The salvage cost has two components *viz*. battery recycle cost and battery reserved value at the end of the evaluation period. The battery recycle cost is adopted with respect to the battery replacement behavior. If the relative capacity of the battery drops below 0.8 owing to degradation at the end of year i, then the old battery should be removed from the vehicle, $z_{\text{off}}(i) = 1$. The user will receive cash for the disposal of the battery. If the battery's reserved price is P_{res} RMB/kWh and the battery energy is e kWh, the refund is $P_{\text{res}} \cdot e$ RMB. The first term of Equation (6) gives the total battery recycle refund with the minus sign signifying the "refund." The battery reserved value at the end of the evaluation period is adopted with respect to the battery's final state assessment. It is also equal to the battery reserved price multiplied by the battery energy. However, the battery reserved value only occurs at the end of the evaluation period, shown as the second term in Equation (6) below:

$$C_{\text{salv}} = -\sum_{i=0}^{N} \frac{P_{\text{res}}(i_{\text{batt}}) \cdot e_{\text{batt}} \cdot z_{\text{off}}(i)}{(1+t)^{i}} - \frac{P_{\text{res}}(i_{\text{batt}}) \cdot e_{\text{batt}}}{(1+t)^{N}} \tag{6}$$

Hence, the battery reserved price P_{res} and the battery replacement decision $z_{\text{off}}(i)$ are essential for calculating the salvage cost and both are based on the degradation model of the battery. The battery degradation model includes both a cycle degradation model and a calendar degradation model. As reference [20] suggests, it is still not clear whether storage or usage of the battery leads to faster capacity fade. The test result in the reference shows very similar degradation trends for both an idle battery and a cycled battery. Based on the conclusion, the effects of cycle degradation and idle degradation cannot be simply summed together. For any given period, only one of the degradation effects should be applied to the evaluation. Thus, the cycle degradation model accounts for the driving days in a year, and the calendar degradation model accounts for the idle days in a year. The battery reserved price P_{res} equals to the initial battery price minuses the degraded price, shown as Equation (7):

$$P_{\text{res}}(i_{\text{batt}}) = P_{\text{batt}} - P_{\text{cyc}} \cdot (c_{\text{drive}} + c_{\text{charge}}) \cdot i_{\text{batt}} - P_{\text{cal}} \cdot i_{\text{batt}} \cdot (1 - \frac{d_{\text{drv}}}{365}) \quad (7)$$

where the first term is the initial battery price, the second term is the cycle degradation price, and the last term is the calendar degradation price. P_{cyc} (unit: RMB/(kWh·Ah)) indicates the degradation price caused by battery charge and discharge cycle. It equals to the price reduction whenever 1 Ah of capacity is charged to or discharged from the battery. c_{drive} and c_{charge} are the yearly cumulative charge and discharge capacity, respectively for the drive phase and charge phase. P_{cal} (unit: RMB/(kWh·year)) indicates the degradation price caused by calendar aging. It equals to the price reduction when the battery stays idle for a year. The cycle and calendar degradation co-contribute to the overall degradation. The weighting factors for both degradation corresponds to the vehicle driving days and idle days in the year.

The cycle degradation model used in this study is based on the charge and discharge capacity during the battery lifetime, which is proposed by the battery research group from the author's lab and applied to several lithium-ion batteries [14]. The relative capacity of the battery degrades with usage (current). Based on the experimental data, the relative capacity reduction caused by battery cycle usage could be expressed as a function g of the charge and discharge capacity during the cycle tests. Equation (8) is the core the referred degradation model, which indicates the life fading along with the usage of the battery:

$$c_{\text{res}} = c_{\text{life}} - \int |I_{\text{batt}}| d\tau \quad (8)$$

where the c_{res} is the residual capacity, and c_{life} is the lifetime capacity from the battery cycle life experiment, I_{batt} is the battery current and τ is the test time. This simple degradation model gives a method of quick evaluation on the residual charge and discharge capacity of the battery, and can be easily extended to the residual price and cost.

To evaluate the relative capacity reduction at the end of the year i_{batt} in real driving, the total charge and discharge capacity of the specific battery could be used as an input of the fitted function g, shown as Equation (9):

$$c_{\text{rer-cyc}} = 1 - g((c_{\text{drive}} + c_{\text{charge}}) \cdot i_{\text{batt}} \cdot \frac{d_{\text{drv}}}{365}) \quad (9)$$

Commonly, when the relative capacity of a battery drops below 0.8, its use as a vehicle power battery is terminated. The initial battery value is equal to the expense of buying it. After its lifetime on the vehicle, the battery is still of value because of either the recyclable materials or the possible secondary use [21]. Degradation cost is defined as the difference between the initial expense and the refund for the degraded battery. Battery degradation price caused by cycle charge and discharge is defined by Equation (10), where p_{end} is the proportion of the battery value reserved at the end of the life (20%, suggested by [21]) and c_{life} is the total charge and discharge capacity available in the battery lifetime:

$$P_{\text{cyc}} = \frac{P_{\text{batt}} \cdot (1 - p_{\text{end}})}{c_{\text{life}}} \quad (10)$$

The battery usage intensity model is a charge and discharge capacity based model to be compatible with the cycle degradation model. The battery capacity usage is divided into two phases, viz. the driving phase and the charging phase.

In the driving phase, the annual charge and discharge capacity calculation is referred to the fuel consumption calculation, utilizing the utility factor. The charge and discharge capacity consumptions for the CD and CS stages are respectively denoted by c_{CD} and c_{CS}, respectively. It is equal to the integration of the absolute current through the cell divided by the corresponding range travelled by the vehicle, shown as Equation (11). The annual driving phase capacity is estimated from:

$$c_{\mathrm{drive}} = [c_{\mathrm{CD}} \cdot \mathrm{UF}(R_{\mathrm{CD}}) + c_{\mathrm{CS}} \cdot (1 - \mathrm{UF}(R_{\mathrm{CD}}))] \cdot R_{\mathrm{avg}} \cdot d_{\mathrm{drv}} / 100 \tag{11}$$

For the charging phase, the delta SOC within a day is used to estimate the charge capacity. For a daily range equal to or shorter than the CD range, the battery charge capacity varies linearly with the daily range and for a daily range longer than the CD range the charge capacity is a constant, equal to the SOC window multiplied by the cell capacity. The annual charge capacity in the charge phase is then calculated using Equation (12), which is also involved with daily driving range distribution $f(r)$:

$$c_{\mathrm{charge}} = [\int_0^{R_{CD}} \frac{r}{R_{\mathrm{CD}}} \cdot (\mathrm{SOC}_{\mathrm{full}} - \mathrm{SOC}_{\mathrm{CS}}) \cdot c_{\mathrm{batt}} \cdot f(r) \cdot \mathrm{d}r + \int_{R_{CD}}^{+\infty} (\mathrm{SOC}_{\mathrm{full}} - \mathrm{SOC}_{\mathrm{CS}}) \cdot c_{\mathrm{batt}} \cdot f(r) \cdot \mathrm{d}r] \cdot d_{\mathrm{drv}} \tag{12}$$

The calendar degradation model of the battery used in this paper is a classic $t^{0.5}$ based model [20,22]. The relative capacity reduction for the idle battery at the end of year i_{batt} could be expressed as:

$$c_{\text{rer-cal}} = 0.00089 \cdot (i_{\mathrm{batt}} \cdot (1 - \frac{d_{\mathrm{drv}}}{365}))^{0.5} \tag{13}$$

where $c_{\text{rer-cal}}$ is the relative capacity reduction, i_{batt} is the years served by the battery, and d_{drv} is the days when the user drives the vehicle. Based on the equation, the calendar age of the idle battery i_{life} could be derived (the life ends when the capacity drops below 0.8). Then the battery degradation price caused by calendar aging is denoted by:

$$P_{\mathrm{cal}} = \frac{P_{\mathrm{batt}} \cdot (1 - p_{\mathrm{end}})}{i_{\mathrm{life}}} \tag{14}$$

After above calculations, the battery reserved price could be calculated via Equation (7). The next issue is the determination of battery replacement. Let i_{batt} represent the number of years served by the current battery, the battery replacement decision $z_{\mathrm{on}}(i)$ and $z_{\mathrm{off}}(i)$ will be made based on the relationship between relative capacity and 0.8, shown as Equation (15). There are exceptions at year 0 and year N. At year 0, only $z_{\mathrm{on}}(0) = 1$, indicating the initial purchase of the battery; at year N, no battery replacement takes place, so both indicators are equal to zero:

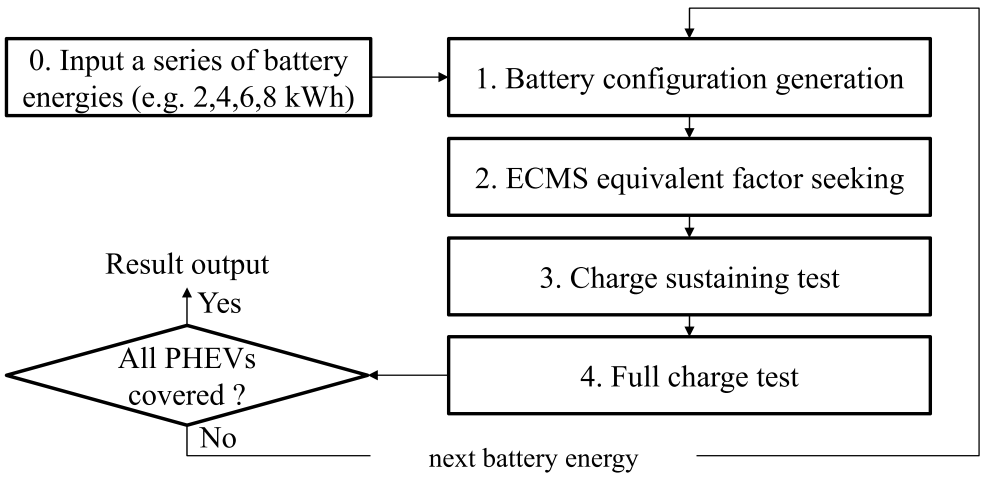
$$z_{\mathrm{on}}(i), z_{\mathrm{off}}(i) = \begin{cases} 0, \text{ when } 1 - c_{\text{rer-cyc}} - c_{\text{rer-cal}} \geq 0.8 \\ 1, \text{ when } 1 - c_{\text{rer-cyc}} - c_{\text{rer-cal}} < 0.8 \end{cases} \tag{15}$$

2.6. PHEV Simulation

The vehicle studied in this paper is a typical parallel plug-in hybrid compact sedan with a vehicle mass (excluding battery) of 1200 kg. The 1.5 L engine has a peak power of 63 kW and the motor has a peak power of 60 kW. The driving cycle used in the study is NEDC, as it is the official certificated driving cycle in China. In this study, the vehicle configurations are fixed except for the size of the battery. As the battery model is a cell-based model, the size of the battery corresponds to both numbers and arrangements of the battery cells. The PHEV simulation model is a quasi-static powertrain model developed for studying the PHEV energy management strategy. For more details of the model, please refer to [23].

The original PHEV model is now integrated into a calculation diagram designed for the TCO model, shown in Figure 3. It is capable of automatically simulating the fuel economy indices for PHEVs equipped with different battery sizes.

Figure 3. Automatic PHEV simulation loop with different battery sizes.



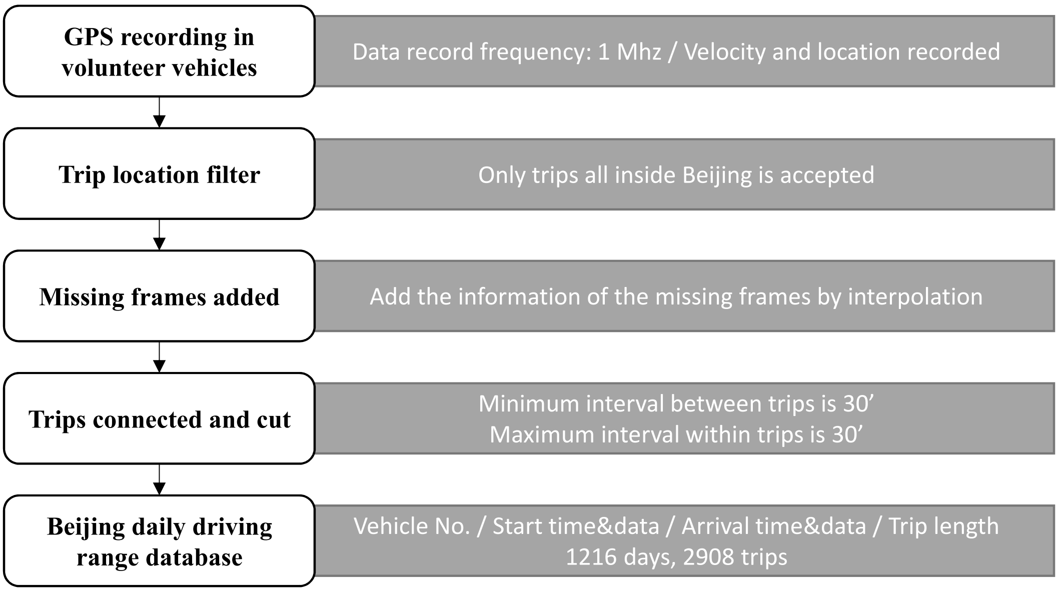
The input of the diagram is a vector of specified battery size (in terms of energy), e.g., 2, 4, 6 kWh. Different battery energies correspond to different all electric ranges and charge depleting ranges (e.g., PHEV 10/20/40). The model will at first provide the battery cell arrangement to ensure a high but allowable voltage. Then, it searches for the optimal "all-electric, charge-sustaining" (AECS) strategy because the strategy is demonstrated to be optimal for PHEVs in regular use [24]. The key factor in the AECS strategy is the equivalent factor of the ECMS strategy at the CS stage. The simulation model seeks to obtain the factor through iterations. Third, the vehicle model goes into the charge sustaining test where the fuel consumption, electricity consumption, and capacity consumption of the CS stage are tested. Fourth, the full charge test is simulated where the fuel economy indices of the CD stage and the charge depleting range are tested. The four steps are implemented sequentially for the given battery sizes. When the simulations for all given PHEVs are completed, the result will be output to the TCO model.

2.7. Daily Driving Range Database

The daily driving range data is from a GPS based survey conducted by the authors' team. The data is collected from 112 volunteer vehicles between June 2012 and March 2013 in Beijing. A total of 4892 trips taken in 2003 days are included in the data. The total range of the collected data is about 100,000 km. The origins and destinations of the trips have been examined, and they are well distributed in the City of Beijing. Thus, the data used in this paper is regarded to be able to represent the driving activities of the passenger vehicles in Beijing. For more details on the database, please refer to Wu's dissertation [15] and [25].

The daily driving range database is completely independent of the TCO model. The database was established to illustrate the driving pattern of the passenger vehicles in Beijing and the range data was stored in the form of "trips" [15]. The original data is collected from volunteers, and then stored in a raw material database. The raw data is not ready for use until it goes through the pre-process of the recorded data described in the next paragraph, illustrated as Figure 4.

Figure 4. The daily driving range database pre-process.



First, the data is filtered by location and only the trips taken strictly inside the city of Beijing are accepted. Then, the missing frames of the recorded data are added by linear interpolation. The missing piece of the velocity curve is considered as a straight line between the two nearest existing data points. Next, some of the original trips need to be "connected" and some need to be "cut". The minimum time interval between trips is 30 min. If the interval between two original trips is less than 30 min, they need to be connected to form a new single trip whereas if an original trip contains an interval of more than 30 min, it is cut into two single trips. After the re-organization, the trips are restored to the database, with the attributes of vehicle number, start date and time, arrival date and time, trip length, *etc.* Utilizing the database, the daily driving range distribution for Beijing passenger vehicles can be generated which is subsequently used in the TCO core model.

Due to the limitation of travelling data, the number of driving days is assumed as 365 in a year and the number of idle days is assumed as 0. On one hand, the user does not travel every day in the year;

on the other hand, the long range travels are not included in the database. Therefore, it is assumed that the impacts of the long trip days and the no-trip days cancel each other out, and the number of driving days in a year is still assumed to 365.

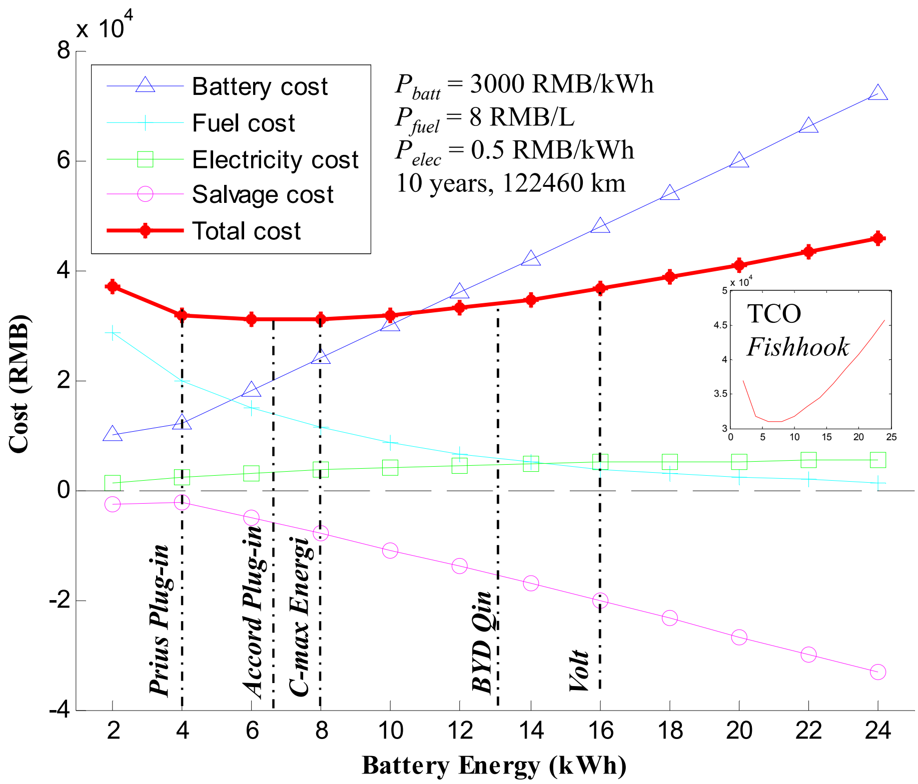
3. Baseline Analysis

The baseline scenario refers to the real scenario of Beijing. The main parameters used in the baseline analysis are listed in Table 1. 12 battery sizes varying from 2 kWh to 24 kWh are analyzed using the TCO model. The result is shown in the form of a TCO curve in Figure 5. According to the figure, the battery energy of 6–8 kWh corresponds to the minimum TCO; thus, it is regarded as the optimal battery size for PHEVs used in Beijing.

Table 1. Parameters for baseline scenario.

Parameters	Value	Source
Battery rate	3000 RMB/kWh	Feng *et al.* [14]
Fuel price	8 RMB/L	Market value
Electricity price	0.5 RMB/kWh	Market value
Discount rate	0.06	Al-Alawi and Bradley [8]
Evaluation period	10 years	Hao *et al.* [26]
Battery end rate proportion	0.2	ANL Report. [21]

Figure 5. TCO and sub-costs curves for the baseline scenario.



The TCO curve (TCOs for different battery sizes) appears to have a convex trend. The minimum TCO of 31,000 RMB is reached at the battery energy of 6–8 kWh. The TCO for the 2 kWh PHEV is about 37,000 RMB, while the TCO for 24 kWh is about 45,700 RMB. The highest TCO is 47% more than the lowest one. By zooming in on the y-axis, it can be seen that the shape of the TCO curve has a very clear fishhook shape as shown in the sub-picture in Figure 5.

Several typical PHEVs are also shown in Figure 5. The usage scenarios of these vehicles are assumed to be exactly the same as the baseline scenario. Thus, the difference among their TCOs is caused only by different battery sizes. The previously published data of the Prius Plug-in [27] and Volt [28] are far from the optimal interval, but the recent vehicles, including the Accord Plug-in [29], C-max Energi [30], and BYD Qin [31] are much closer to the optimal interval.

The four sub-costs of the total cost have different trends due to the following reasons:

The battery cost increases almost linearly with the battery energy except for the battery energy of 2 kWh. For PHEVs having battery energy of 2 kWh, the battery cells usually work at large currents, which accelerate the battery's degradation. Hence, the battery needs to be replaced at the end of the 7th year.

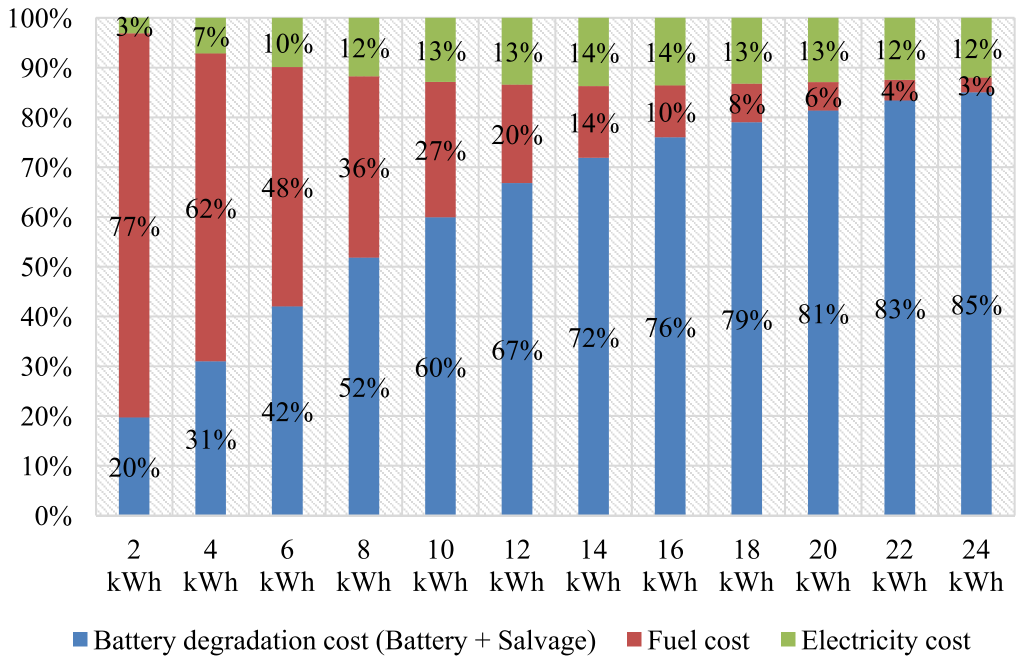
The fuel cost decreases with an increase of the battery energy but the slope of the decrement becomes smaller and smaller. For example, the fuel cost at 4 kWh battery energy is 4700 RMB higher than that at 6 kWh, but the fuel cost at 14 kWh battery energy is only 1200 RMB higher than that at 16 kWh. Though the charge depleting range increases almost linearly with the battery energy, the increment in the corresponding utility factor becomes lower with an increase in the charge depleting range. In other words, the decrement of the slope of the utility factor curve is responsible for the trend of the fuel cost curve.

The electricity cost has the opposite trend of fuel cost. With the increase of the battery size, the corresponding utility factor UF ($R_{\mathrm{CD}}(e)$) increases. According to Equations (3) and (5), the fuel cost decreases and the electricity cost increases. However, the increment of the electricity cost is less than the decrement of the fuel cost because of two reasons. First, the electric powertrain has a higher efficiency than the internal combustion engine efficiency. Referring to a previous study [23], the vehicle drive efficiency of the engine powertrain in the PHEV is approximately 30% and that of the electric powertrain is about 85%. For a certain driving pattern, the energy demand is fixed. The sum of the energy output by both engine powertrain and electric powertrain is a constant. However, due to the difference of the powertrain efficiency, 1 unit of the input fuel energy only corresponds to about 0.3 unit of the energy demand, which could be offset by only 0.35 unit of input electric energy. Second, the electricity price looks much lower than that of the fuel, but they are substantially very close. Converting the fuel price to the energy based unit by counting the low heating value of the gasoline, the fuel price is round to 0.5 RMB/kWh, which is very close to the electricity price. As a summary, referring to Equations (3) and (5), with the same driving pattern, the increase of the battery size will introduce an increment to average electricity consumption (AEC) and a decrement to the average fuel consumption (AFC), and the increased electric energy consumption is much less than the decreased fuel energy consumption. And because the energy based prices of the fuel and electricity are very close, the increment of electricity cost is less than the decrement of fuel cost.

The absolute value of the salvage cost increases linearly with the battery energy also except for the PHEV with 2 kWh battery energy. As mentioned earlier, the PHEV has the expenditure of an additional battery. Thus, the salvage cost of the PHEV equipped with a 2 kWh battery includes both the old battery recycle cost and the reserved value for the second battery at the end of the evaluation period whereas the others only have the reserve value at the end of the evaluation period.

Figure 6 illustrates the percentages of the sub-costs. The battery degradation cost, which is the sum of the battery cost and the salvage cost, represents the net expenditure on the battery. For battery energies less than 6 kWh, the fuel cost is the major cause of high TCO, exceeding 50% of TCO. For battery energies more than 8 kWh, the battery degradation cost (battery cost plus salvage cost) is the major cause of high TCO, exceeding 50% of TCO. For all PHEVs, the electricity cost occupies no more than 14% of TCO.

Figure 6. Sub-cost percentages.



As illustrated in Section 2.1, the TCO model is based on the cash flow structure during the evaluation period. Table 2 lists the discounted cash flows for PHEVs with 2, 4, 8, 16 kWh battery energies, which respectively correspond to PHEV5, PHEV10, PHEV20, and PHEV40. According to the table, it is seen that at Year 0, the only cash flow belongs to the battery cost. The battery cost cash flow does not appear anywhere except for PHEV5 owing to the battery replacement at the end of the 7th year. Another feature is that the salvage cost always appears at the end of the evaluation period; it refers to the battery reserved value as explained in Section 2.5. All values in the table are discounted values. The discount rate for each year is listed in the second row of the table.

Table 2. The cash flows for the sub-costs during the evaluation period.

Vehicle Configuration	**Year**	0	1	2	3	4	5	6	7	8	9	10
	Discount rate	1.00	0.94	0.89	0.84	0.79	0.75	0.70	0.67	0.63	0.59	0.56
PHEV 5 (TCO = 37,152 RMB)	Battery cost (RMB)	6000	0	0	0	0	0	0	3990	0	0	0
	Fuel cost (RMB)	0	3657	3450	3255	3070	2897	2733	2578	2432	2294	2165
	Electricity cost (RMB)	0	147	138	131	123	116	110	103	98	92	87
	Salvage cost (RMB)	0	0	0	0	0	0	0	–440	0	0	–2073
	Total cost (RMB)	6000	3804	3588	3385	3194	3013	2842	6232	2530	2386	178
PHEV 10 (TCO = 31,956 RMB)	Battery cost (RMB)	12,000	0	0	0	0	0	0	0	0	0	0
	Fuel cost (RMB)	0	2519	2376	2242	2115	1995	1882	1776	1675	1580	1491
	Electricity cost (RMB)	0	292	275	260	245	231	218	206	194	183	173
	Salvage cost (RMB)	0	0	0	0	0	0	0	0	0	0	–1974
	Total cost (RMB)	12,000	2811	2652	2502	2360	2227	2101	1982	1869	1764	–310
PHEV 20 (TCO = 31,224 RMB)	Battery cost (RMB)	24,000	0	0	0	0	0	0	0	0	0	0
	Fuel cost (RMB)	0	1447	1365	1288	1215	1146	1081	1020	962	908	856
	Electricity cost (RMB)	0	467	440	415	392	370	349	329	310	293	276
	Salvage cost (RMB)	0	0	0	0	0	0	0	0	0	0	–7704
	Total cost (RMB)	24,000	1913	1805	1703	1607	1516	1430	1349	1273	1201	–6571
PHEV 40 (TCO = 36,775 RMB)	Battery cost (RMB)	48,000	0	0	0	0	0	0	0	0	0	0
	Fuel cost (RMB)	0	487	459	433	409	386	364	343	324	305	288
	Electricity cost (RMB)	0	636	600	566	534	503	475	448	423	399	376
	Salvage cost (RMB)	0	0	0	0	0	0	0	0	0	0	–19982
	Total cost (RMB)	48,000	1122	1059	999	942	889	839	791	747	704	–19318

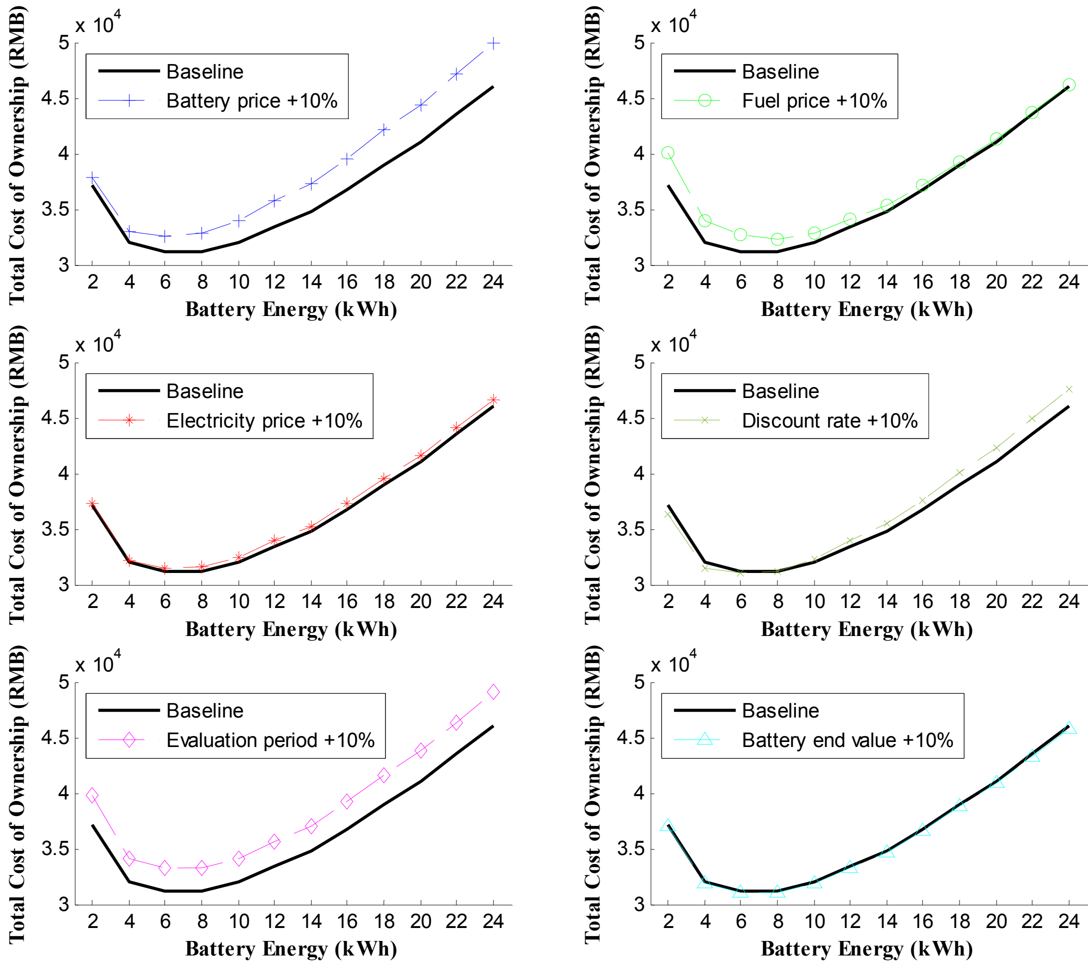
4. Scenario Analysis

4.1. Sensitivity Analysis

In this section, the sensitivity analysis of the six economic parameters of the TCO model will be implemented one by one. The sensitivity analysis is based on the baseline scenario. Only one of the parameters is increased by 10% each time and the other parameters remain the same to the baseline. The TCO curve with the increased parameters is compared to the baseline TCO curve side by side. The baseline values and the increased values of the six parameters are listed in Table 3.

Figure 7 shows the TCO curve comparisons for the six parameters. An increase in battery price generally increases the TCO. The more the energy of the installed battery is, the more the TCO increases. An increment of 10% in the battery price will only increase the TCO of a 2 kWh PHEV by 2%, while the same change in battery price will increase the TCO of a 24 kWh PHEV by 8%. Thus, the optimal battery energy shifts to 6 kWh. An increase in fuel price also increases the TCO. However, the trend of fuel price is different from that of battery price. The less the energy of the installed battery is, the more the TCO increases. For example, a 10% increment in fuel price will contribute 7.5% to the TCO for a 2 kWh PHEV, but it will only contribute 0.2% to the TCO for a 24 kWh PHEV. An increase in the fuel price will result in the optimal battery energy of 8 kWh. An increment in the electricity price will slightly increase the TCO. The more the battery energy is, the more the TCO increases.

Figure 7. The sensitivity analysis.



As a result, the optimal battery energy is 6 kWh. An increase in the discount rate will increase the TCO for large batteries but will reduce the TCO for small batteries. A higher discount rate will induce both lower fuel cost and less absolute salvage cost. Both results benefit small batteries. As a result, 6 kWh is the optimal battery size if the discount rate is increased by 10%. Increments in the remaining two parameters do not have any impact on the battery size, though they somehow affect the TCO. The evaluation period being independent of the battery size is an advantage of this TCO model and this can be attributed to the introduced salvage cost model.

Table 3. Sensitivity analysis table.

Parameter	Baseline	Increased	Comparison
Battery price (RMB/kWh)	3000	3300	10%
Fuel price (RMB/L)	8	8.8	10%
Electricity price (RMB/kWh)	0.5	0.55	10%
Discount rate	0.06	0.066	10%
Evaluation period (year)	10	11	10%
Battery end relative value	0.2	0.22	10%

4.2. Driving Range Distributions

The daily driving range distribution is one of the most important factors impacting on the energy cost of a PHEV. In this section, the daily range distribution of the U.S. will be applied to the model to compare it with the Beijing baseline scenario. In order to address the impact of the daily driving range distribution, other parameters are kept the same as the baseline Beijing scenario, though they are actually different between Beijing and U.S. The daily driving range data of Beijing has already been explained in Section 2.7. The daily driving range data of the U.S. is derived in the reverse direction from the utility factor curve specified in SAE J2841 [18]. Based on a study by Lin [16], the daily driving range distribution can be expressed as a Gamma distribution with parameters a and b. The probability density function (PDF) is shown in Equation (16):

$$f(r \mid a,b) = \frac{1}{b^a \Gamma(a)} r^{a-1} e^{\frac{-r}{b}} \tag{16}$$

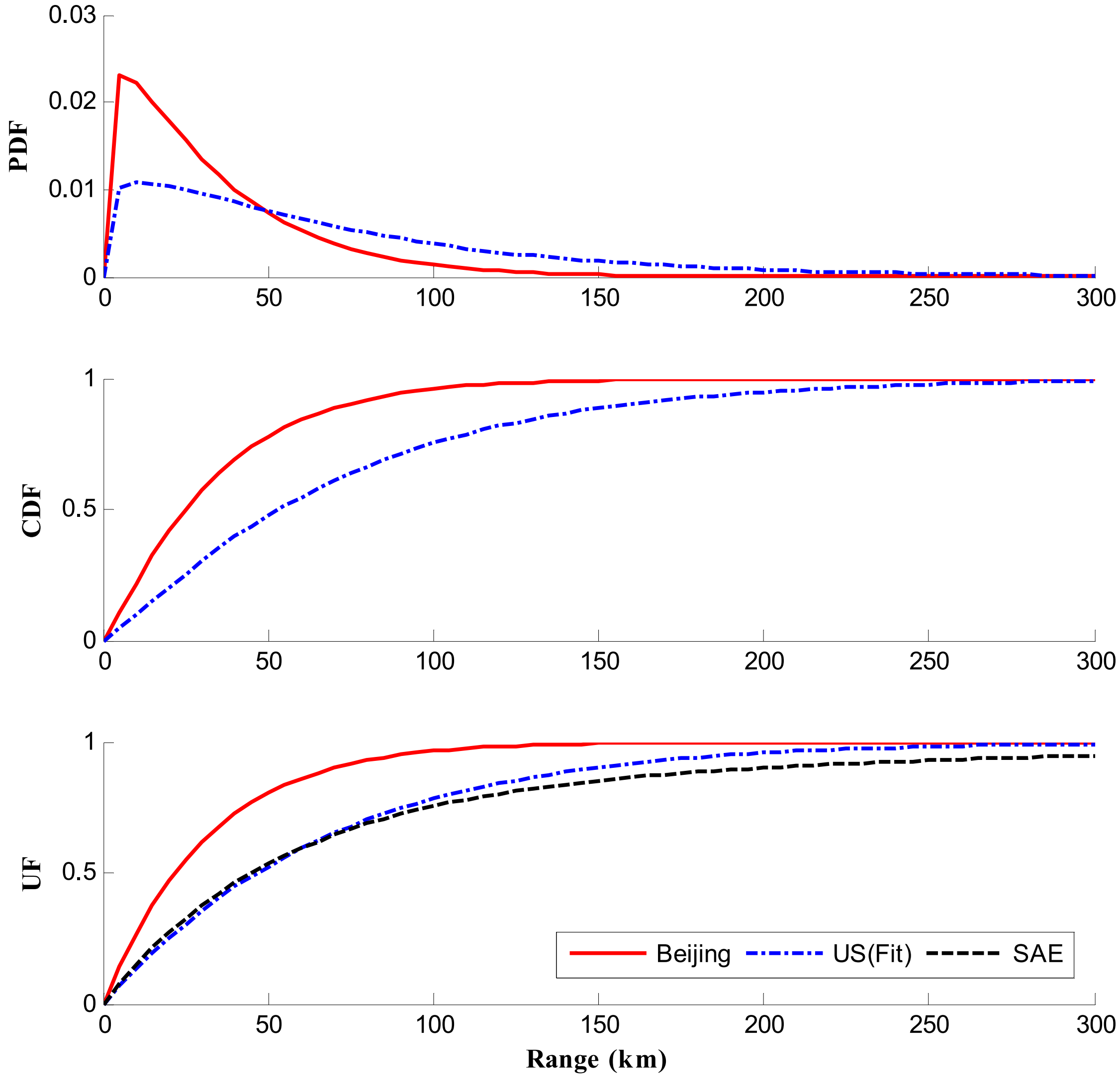
Based on the previous studies, the utility factor curve can be converted from the PDF [17]. The parameters a and b of the U.S. daily driving range distribution is found via the method of iteration. The parameters of Beijing are used as the initial guess of the parameters of the U.S. Using the least-square estimation, when the sum of the squares of differences between the fitted UF curve and the SAE prescribed curve reaches the minimum, the gamma distribution with the corresponding parameters a and b is considered as a good estimation of the daily driving range distribution in the U.S. The parameters of the U.S. daily driving distribution are listed in Table 4.

Table 4. Sensitivity analysis table.

Location	Parameter *a*	Parameter *b*
Beijing	1.20	27.87
U.S.	1.21	59.58

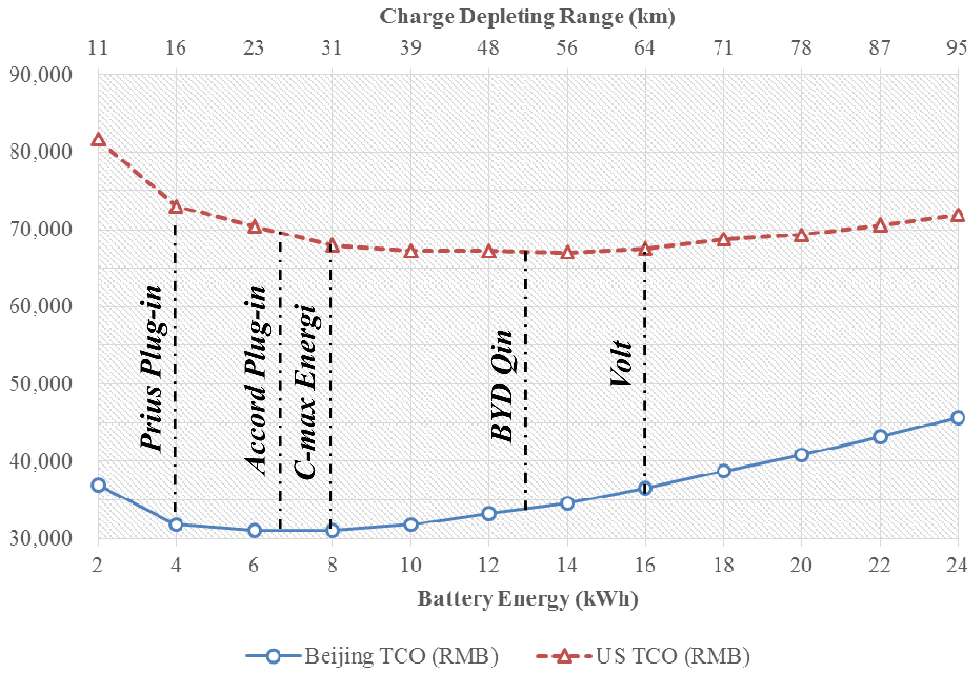
Using the fitted parameter, the probability density functions, cumulative distribution functions, and the utility factor curves of both Beijing and U.S. are plotted in Figure 8. As far as we know, the average daily driving distribution in the U.S. is longer than in Beijing while the daily driving range is less concentrated in the U.S. than in Beijing because the PDF peak is lower. The CDF shows that 77.8% of trips in Beijing are within 50 km, while only 47.6% of the trips in U.S. are within 50 km.

Figure 8. Daily range distribution comparison between Beijing and U.S.



Utilizing the estimated daily driving range distribution in the U.S. and the TCO model described in Section 2.1, the TCO curve of the PHEVs used in the U.S. is calculated and shown in Figure 9. The optimal battery energy of the PHEV in the U.S. is 14 kWh, which is nearly twice the optimal battery energy in Beijing. The TCO curve of U.S. is generally higher than that of Beijing because of the longer daily driving distance in the U.S. The typical PHEV products are also shown in Figure 9. The Chevy Volt has the second lowest TCO compared to other products in the U.S., though it has the highest TCO in Beijing. The comparison shows the necessity of optimal design of the battery size in different regions.

Figure 9. TCO curve comparison between Beijing and U.S. range distributions.



4.3. Subsidy

All over the world incentives are provided for the promotion of PHEVs and this has a great impact on the optimal battery size. For example, the latest subsidy policy in China was released in September 2013. For PHEVs with an all-electric range longer than 50 km, the subsidy for the vehicle is constant at 35,000 RMB [32]. The subsidy in the U.S. is different from that in China. A PHEV is not eligible for a subsidy from the U.S. government unless a battery larger than 5 kWh is installed in the vehicle. The basic credit for an eligible PHEV is $2500. With a battery energy exceeding 5 kWh, a PHEV is eligible for a credit at the rate of $417/kWh. The maximum credit for a vehicle is $7500, corresponding to the battery energy of 17 kWh [33].

From the perspective of credit calculation, the subsidy policies can be classified into three categories: (1) vehicle based: for an eligible vehicle, the credit for a vehicle is a constant, similar to the policy in China; (2) battery energy based: the credit is fully or partially linear with the battery energy, similar to the policy in U.S.; (3) fuel saving based: the credit is linear with the fuel saving rate compared to that for conventional vehicles. The third policy for PHEVs is innovatively proposed in this study. The average fuel consumption (AFC) introduced in Section 2.3 is used to evaluate the fuel consumption of PHEVs. The fuel consumption of a comparable CV is estimated to be 8 L/100 km from the simulation. The fuel saving rates for PHEVs is then calculated based on above indices.

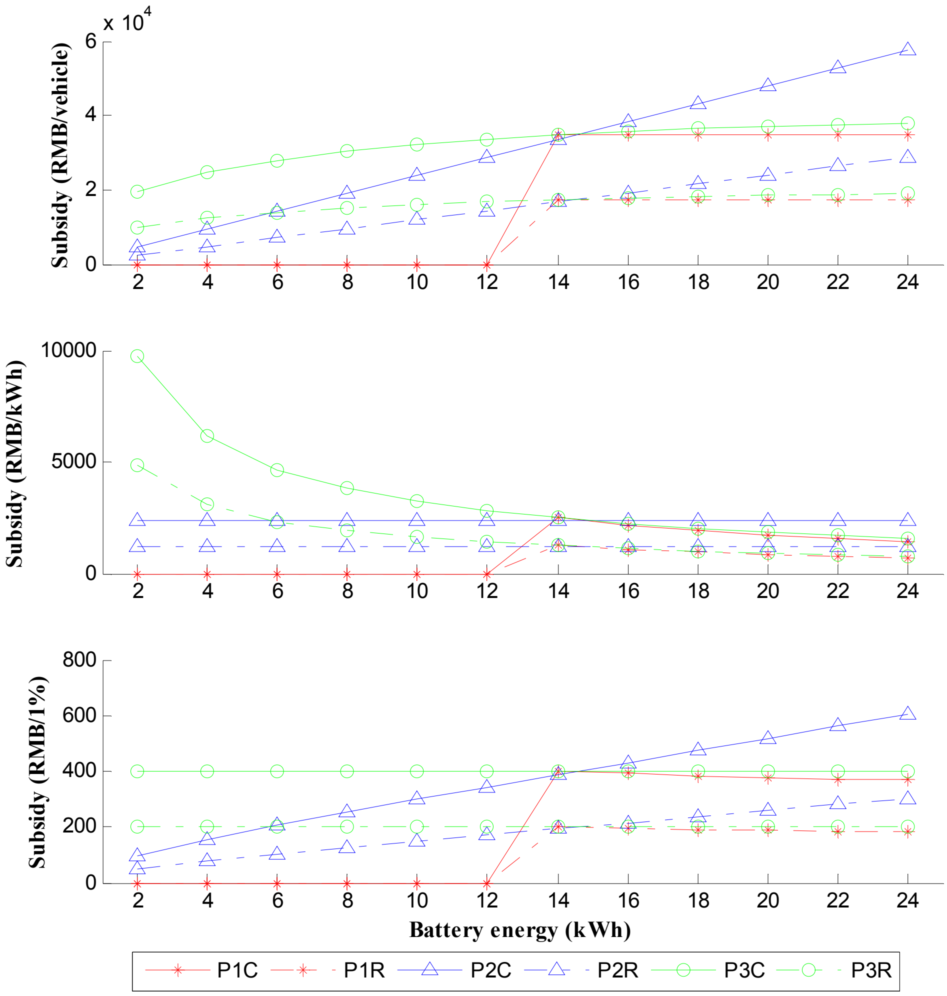
The three categories of policies are applied to the Beijing scenario and compared in this paper, as listed in Table 5. For each of the policies, two proposals are involved. The current proposal is made equivalent to the latest subsidy policy in China, which indicates that a PHEV with the all-electric range (AER) of 50 km receives a credit of 35,000 RMB. The other details in the reduced proposal remain unchanged while reducing the credit to half.

Table 5. Subsidy policies.

Policy	Proposal	Symbol	Description
Policy 1	Current (C)	P1C	AER ≥ 50 km, 35,000 RMB/vehicle
	Reduced (R)	P1R	AER ≥ 50 km, 17,500 RMB/vehicle
Policy 2	Current (C)	P2C	Based on battery energy, 2400 RMB/kWh
	Reduced (R)	P2R	Based on battery energy, 1200 RMB/kWh
Policy 3	Current (C)	P3C	Based on fuel saving, 400 RMB/1%
	Reduced (R)	P3R	Based on fuel saving, 200 RMB/1%

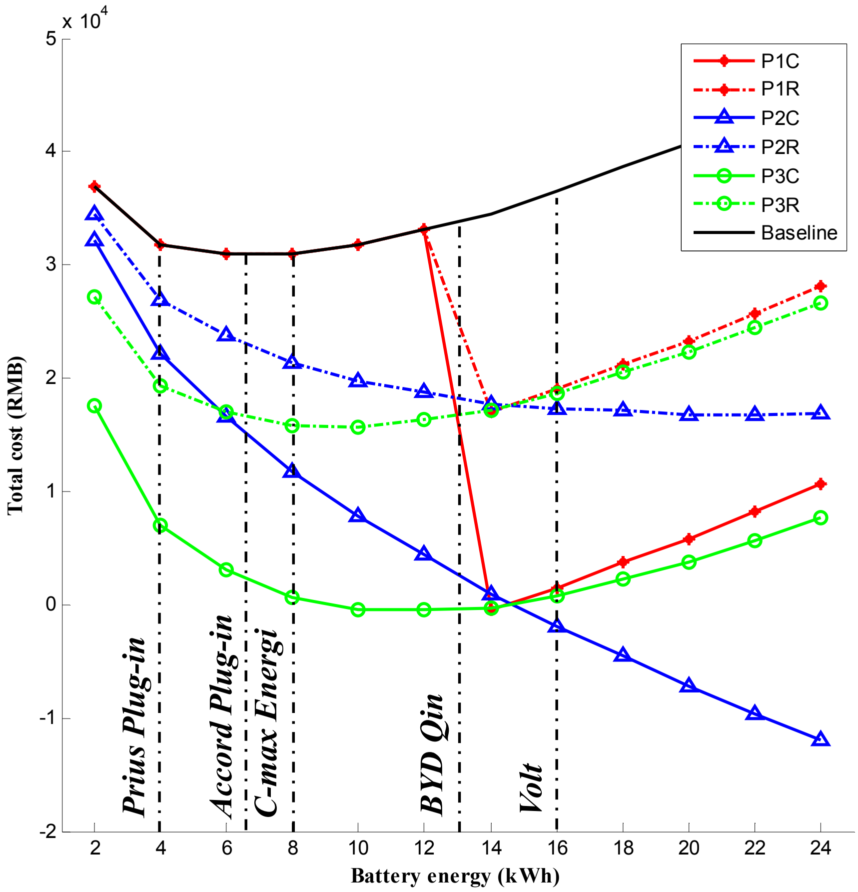
Figure 10 shows the three policies in three different perspectives. The top sub-figure is illustrated from the perspective of subsidy gained by the vehicle. The figure shows that Policy 2 results in the largest credit difference for vehicles with large battery sizes, followed by Policy 3. The medium sub-figure depicts the subsidy distributed per battery energy. It suggests that Policy 3 will distribute a quite high credit for PHEVs with small batteries. In other words, the fuel savings brought by per battery energy is larger in PHEVs with smaller batteries than in those with larger batteries. The bottom sub-figure is plotted from the perspective of the credit paid for each percentage of the fuel saving rate. From the figure, if Policy 2 is applied, the cost of achieving a fuel saving of 1% by the government will increase dramatically with increase in the battery energy.

Figure 10. Policy illustration with three different perspectives.



Different policies will have different impacts on the TCO curve as well as on the optimal battery size, as shown in Figure 11. Policy 1 introduces a sudden sink to the TCO curve. As a result, the optimal battery size corresponds to the "just eligible" battery energy. The simulation results of this study show that the 12 kWh and 14 kWh correspond to the AERs of 48 km and 57 km, respectively, as shown in Figure 9. The 50 km corresponds to approximately 13 kWh. The analysis can be a reason for the increase in battery size from 10 kWh to 13 kWh in BYD Qin [31]. Policy 2 completely changes the TCO curve from the original convex curve with a minimum value to a monotonous decreasing curve. In other words, the larger the installed battery is, the more beneficial the subsidy is to the user. This could be a possible reason why the Chevy Volt with the largest battery has better sales than other PHEVs in the US. As the subsidy in the U.S. has a maximum of $7500, which corresponds to the battery size of 17 kWh, the 17 kWh battery energy is regarded as the practical optimal battery size for the U.S. market.

Figure 11. TCO curves after subsidy.



In accordance with the above analysis, both Policy 1 and Policy 2 dramatically change the original TCO curve. The disturbance of the policy does not have a good impact on the market competition. The ideal subsidy policy should treat all techniques and methods equally only with regard to fuel saving. Policy 3, a fuel saving based subsidy policy, is regarded as an unbiased subsidy policy for PHEVs. The TCO curve is still a convex curve after the subsidy; the optimal battery size is 10–12 kWh in accordance with the current proposal and 8–10 kWh with the reduced proposal.

4.4. Battery Type

The $Li_4Ti_5O_{12}$ (LTO) battery is considered as a potential substitute for the widely used $LiFePO_4$ battery because despite its high price, it has a long cycle life and a higher power density [14]. Many buses equipped with LTO batteries are now involved in demonstration programs in China [34]. Table 6 lists several important parameters of the two batteries. The rest of this section compares the TCO curve and the optimal battery size of both types of batteries.

Table 6. Battery characteristics comparison.

Battery type	Battery A	Battery B
Cell type	$LiFePO_4$	LTO
Cell VOC (V)	3.3	2.3
Cell resistance (ohm)	0.0088	0.0028
Cell capacity (Ah)	12.35	20.5
Cell mass (kg)	0.36	0.51
Max Terminal Voltage (V)	3.7	2.8
Min Terminal Voltage (V)	2.5	1.5
Battery price (RMB/kWh)	3000	9000

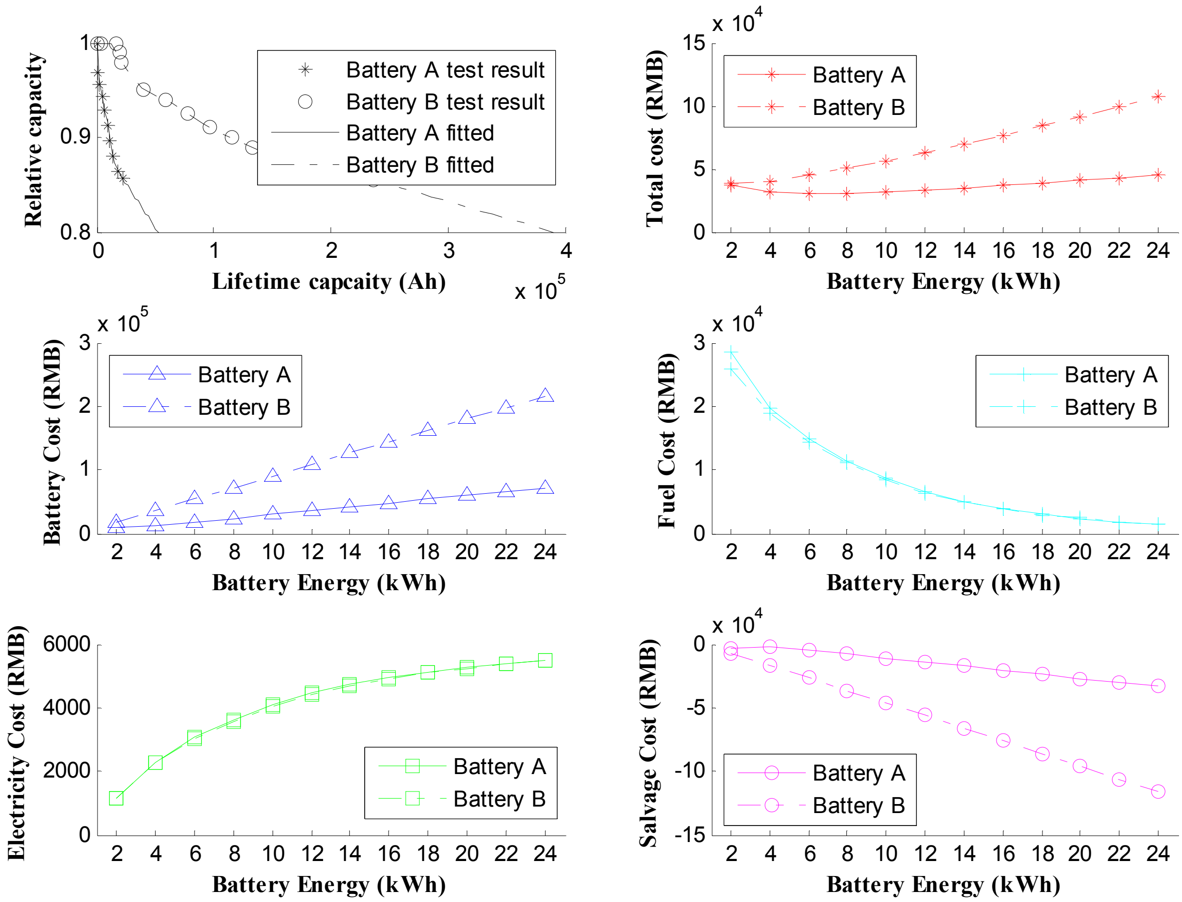
The three characteristics of the LTO battery, *viz*. high price, high power density, and long cycle life, together impact the TCO analysis. A qualitative analysis may infer that the high price increases the battery cost, but the salvage cost is simultaneously higher; the high power density reduces the fuel consumption in the CD stage because it is possible to implement pure electric driven vehicles with small batteries. Further, the long cycle life reduces the possibility of battery replacement and increases the available lifetime capacity.

Then, a quantitative analysis based on the test results from the authors' lab [35] is performed. The battery price of LTO is approximately 9000 RMB/kWh, which is about three times the price of $LiFePO_4$. Based on the data in Table 6, the power density of the LTO is about 1288 W/kg, while that of the $LiFePO_4$ is about 833 W/kg. The lifetime charge and discharge capacity of the $LiFePO_4$ battery is calculated from the lifetime degradation test [35]. The lifetime capacity of the LTO battery is referred to that of Takami [36], because in the result of [35], the capacity of LTO does not have an evident decreasing trend even after 1000 cycles. Finally, the lifetime capacity of LTO is estimated to be 400,000 Ah, which is approximately eight times as that of the $LiFePO_4$ battery, shown in Figure 12. However, it must be borne in mind that some other factors affecting the battery life, such as the charging and discharging rates, the temperature, are not considered in this model for simplicity.

The TCO analyses of both batteries are conducted using the TCO model established in Section 2. The results in Figure 12 show that the optimal battery size for the LTO battery is 2 kWh, which is much smaller than that of the $LiFePO_4$ battery. The TCO curve of PHEVs with LTO batteries increases monotonously with an increase in the battery size. Figure 12 also shows a comparison between the batteries in terms of the TCO sub-costs. The differences between the batteries in the battery cost and the salvage cost are very obvious. The battery cost is directly related to battery price, and thus the battery cost of a LTO battery is three times as high as that of the $LiFePO_4$ battery. However, because of the long cycle life, the battery degradation cost of the LTO battery is lower than that of the $LiFePO_4$

battery. This results in a four times difference in the salvage cost. For the fuel cost, because of the capability of pure electric-driven PHEVs with small LTO batteries, the fuel cost of PHEVs with 2 kWh LTO batteries is 9% lower than that with 2 kWh $LiFePO_4$ batteries. The electricity costs of the two batteries are very similar due to the low electricity price.

Figure 12. TCO comparison between battery types.



5. Conclusions

In this paper, a system level analysis model of the total cost of PHEVs that innovatively integrates the Beijing driving pattern database, the optimal PHEV energy management strategies earlier developed by the author, the battery degradation model developed by the author's team, and the utility factor weighted fuel consumption evaluation proposed by SAE standards, has been proposed. The proposed TCO model is a cash flow model, which includes battery, fuel, electricity, and salvage costs. A battery degradation based salvage model is proposed for the first time. By applying the above model to different scenarios, the following conclusions can be drawn:

(1) The optimal battery size for PHEVs in Beijing is 6–8 kWh based on the real driving pattern database of Beijing. For PHEVs with battery energies less than 6 kWh, the major contributor (>50%) to the TCO is the fuel cost, and for PHEVs with battery energies of more than 8 kWh, the major contributor is the battery degradation cost.

(2) Fuel price and battery price are the two most significant economic parameters in the TCO curve. A 10% increase in fuel price will contribute an additional 7.5% and 0.2% to the TCO of PHEVs with

batteries of 2 kWh and 24 kWh, respectively; a 10% increase in battery price will increase the TCO of PHEVs with batteries of 2 kWh and 24 kWh by 2% and 8%, respectively.

(3) The daily range distribution in the U.S. makes the optimal battery size 14 kWh, which is nearly twice as large as that utilizing the daily range distribution in Beijing.

(4) Under the current Chinese subsidy policy, the optimal battery energy for PHEVs is 13 kWh; under the current U.S. subsidy policy, the optimal battery energy for PHEVs is 17 kWh. A fuel saving based subsidy policy, as a technically un-biased subsidy policy, is proposed in this paper.

(5) The optimal battery size for PHEVs with LTO batteries is 2 kWh. However, the TCO is generally larger than that with $LiFePO_4$ batteries due to the higher battery price.

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Author Contributions

C. Hou establishes the model, calculates the result and drafts the paper; H. Wang provides the travel data analysis and collects other required data; And M. Ouyang provides the idea of TCO analysis and gives instructions to the research;

Abbreviations

AFC	Average fuel consumption (L/100km)
AEC	Average electricity consumption (kWh/100km)
AER	All-electric range (km)
AECS	All-electric, charge sustaining
a	Parameter a in Gamma distribution
b	Parameter b in Gamma distribution
C_{batt}	The battery cost (RMB)
C_{elec}	The electricity cost (RMB)
CD	Charge depleting
C_{fuel}	The fuel cost (RMB)
CS	Charge sustaining
C_{salv}	Salvage cost (RMB)
C_{total}	The total cost (RMB)
c_{batt}	The battery capacity (Ah)
c_{CD}	The charge and discharge capacity consumption in CD stage (Ah/100km)
c_{CS}	The charge and discharge capacity consumption in CS stage (Ah/100km)
c_{charge}	The annual charge and discharge capacity in charging phase (Ah/year)
c_{life}	The charge and discharge capacity available over the life time of battery (Ah)
c_{drive}	The annual charge and discharge capacity in driving phase (Ah/year)
e	Battery energy (kWh)

EC_{CD}	Electricity consumption in the CD stage (kWh/100km)
FC_{CD}	Fuel consumption in the CD stage (L/100km)
FC_{CS}	Fuel consumption in the CS stage (L/100km)
i	The i^{th} year
i_{batt}	The number of years served by the present battery
N	Evaluation years
NPV	Net present value
P_{batt}	Battery price (RMB/kWh)
P_{deg}	Battery degradation rate (RMB/(Ah·kWh))
P_{fuel}	Fuel price (RMB/L)
P_{elec}	Electricity price (RMB/kWh)
P_{res}	Battery reserved price (RMB/kWh)
p_{end}	The proportion of the battery end rate over the initial battery rate
R_{avg}	Average daily range (km)
R_{CD}	Charge depleting range (km)
SOC_{CS}	SOC level where the vehicle sustains the charge
SOC_{full}	SOC when the battery is full charged
r	Daily driving range (km)
T	Discount rate vector in N years
TCO	Total cost of ownership (RMB)
t	The discount rate
UF	Utility factor
z_{on}	The decision of installing a new battery
z_{off}	The decision of disposing an installed battery

Conflicts of Interest

The authors declare no conflict of interest.

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