Cost-Effectiveness Analysis of Plug-In Hybrid Electric Vehicles using Vehicle Usage Data Collected in Shanghai, China

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Abstract
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Keywords
Plug-in hybrid electric vehicles, Driving and charging pattern, Total cost of ownership, Economic viability

Disciplines
Transportation Engineering

Comments
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ABSTRACT

This paper investigates the economic viability of plug-in hybrid electric vehicles (PHEV) in Shanghai, China based on a real-world in-use PHEV dataset. To quantify PHEV drivers’ gross profit compared to internal combustion engine vehicle (ICEV) owners, a total cost of ownership (TCO) model is adopted taking account of vehicle retail price, tax credits, subsidies, insurance, maintenance, energy prices, and resale value. The impacts of the determinants for gross profit are examined in terms of vehicle distance traveled (VDT) electrically, gasoline price, electricity price, and car-buying cost. It is found that (1) only 10% of the deployment of PHEVs (i.e. BYD Qin) is economically viable if the benefit from a free license plate is exempt; (2) the 100-kilometer gross profit of PHEVs increases linearly with the electric driving distance, while the saving of energy cost per kilometer decreases with the total VDT; (3) PHEVs’ profit could be significantly improved by reducing the car-buying cost – a decrease of 10% in car-buying cost makes 80% of the PHEV deployment feasible; (4) if switching the daytime charges to off-peak hours, 50% of the PHEV deployment will become feasible.

Keywords: Plug-in hybrid electric vehicles, Driving and charging pattern, Total cost of ownership, Economic viability
1 INTRODUCTION
Plug-in hybrid electric vehicles (PHEV) offer a promising alternative to internal combustion engine vehicles (ICEV) as they allow for higher powertrain efficiency and lower emissions. Since they are less dependent on charger availability, PHEVs are more attractive to private car owners compared to battery electric vehicles (BEV). Take Shanghai, China as an example, where the local government provides subsidies on PHEVs slightly less than BEVs (i.e. less than ¥10,000 per vehicle) (1), the annual increase of private car ownership for PHEVs was 19,882 in 2016, nearly five times than that for BEVs (i.e. increased by 3,328 vehicles) (2). With regard to ICEVs, which still dominate the Chinese automobile market, the passenger car sales in 2016 were more than 360,000 (3). Unlike ICEVs, PHEVs require new components like electric engine, power electronics, and traction battery, thus, resulting in a higher purchase cost (4). For example, the manufacturer suggested retail price (MSRP) of BYD Qin, a plug-in hybrid compact sedan manufactured by the BYD Auto Company Ltd, is ¥219,800. This price is twice as much as that of BYD G5, which is a conventional gasoline vehicle having the similar size, turbo, horsepower, torque, and auxiliary functions as BYD Qin (5). Although various incentives, like subsidies and tax credits have been provided to promote the acceptance of PHEVs in China and other countries (6), the high expenditure on vehicle purchase hinders the growth of PHEVs’ market share.

The total cost of ownership (TCO) information, including the initial purchase price, operating cost, and salvage value of the vehicle over the lifetime, is often considered to examine the economic and marketplace viability of PHEVs (4, 7-13). TABLE 1 lists the scopes, assumptions and modeled components of the primary and most cited studies. Previous TCO models have several drawbacks. First, the insurance cost and vehicle salvage value are often excluded from the models (4, 7, 10, 12). Since the price difference between PHEVs and their comparable ICEV models are significant, and the insurance cost and salvage value highly correlate with the vehicle price, this approach might lead to uncorrected conclusions. Second, in Shanghai where the number of vehicle license plates issued per month is under strict control, the qualification of PHEVs for dedicated and free license plates raises concerns over challenges of growing auto ownership (6). Some drivers adopt PHEVs because of the free license plate. Due to the limited charging infrastructure, they operate PHEV mostly in charge-sustaining (CS) mode rather than in charge-depleting (CD) mode. However, the impacts of the free license policy are not considered in most studies (4, 7, 10-12). Third, due to the lack of usage data, annual distance traveled by PHEV users are assumed constant (4), or subject to a certain distribution derived from the driving profiles of ICEV users (14), thereby PHEV users’ driving and charging patterns cannot be reflected precisely.

Various programs have been launched to collect and analyze electric vehicles’ usage data, including the U.S. Department of Energy’s EV Project (14), the SwitchEV project (15), the CABLED project (16), the ZeEUS project (17) and so forth. Likewise, cities in China, such as Beijing, Shanghai, and Shenzhen, have developed new energy vehicles (NEVs) monitoring and service platforms. To the best of our knowledge, no TCO analysis for PHEVs has been carried out based on the dataset collected from these platforms. In this paper, we use the data collected by Shanghai Electric Vehicles Data Center (SHEVDC) that is developed to remotely monitor electric vehicles driven across the city. 50 PHEVs, with the same model of BYD Qin, are extracted from the SHEVDC database, and their TCO are examined and compared to a comparable ICEV model (i.e. BYD G5).
### TABLE 1  Review of TCO literature.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Electric Range</td>
<td>4, 12, and 20kWh</td>
<td>32, 64 and 97 km</td>
<td>6, 10, and 14kWh</td>
<td>5-60km</td>
<td>5-40km</td>
<td>16, 32, 48, and 64km</td>
<td>40km</td>
<td>70km (13kWh)</td>
</tr>
<tr>
<td>Reference country</td>
<td>Germany</td>
<td>USA</td>
<td>Germany</td>
<td>USA</td>
<td>China</td>
<td>USA</td>
<td>USA</td>
<td>China</td>
</tr>
<tr>
<td>Vehicle life</td>
<td>10 years</td>
<td>Normal distribution with the mean value of 9 years</td>
<td>4 years</td>
<td>5 and 13 years</td>
<td>10 years</td>
<td>3, 5, and 10 years</td>
<td>5 and 10 years</td>
<td>10 years or when the mileage reaches 600,000km</td>
</tr>
<tr>
<td>Discount rate</td>
<td>8%</td>
<td>6%</td>
<td>5%</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
<td>5%</td>
<td>6%</td>
</tr>
<tr>
<td>Annual vehicle distance traveled model</td>
<td>Based on ICEV users’ driving profile</td>
<td>Log-normally distribution (Med: 19,312)</td>
<td>Based on ICEV users’ driving profile</td>
<td>19,312km/year for car; 24,140km/year for truck, with decline in vehicle usage with age</td>
<td>Based on ICEV users’ driving profile</td>
<td>Based on ICEV users’ driving profile</td>
<td>24,140km/year</td>
<td>Based on PHEV usage data</td>
</tr>
<tr>
<td>Electricity consumption method</td>
<td>Charge simulation</td>
<td>Charge simulation</td>
<td>Charge simulation</td>
<td>Forecasted over vehicle life</td>
<td>Charge simulation</td>
<td>Charge simulation</td>
<td>Constant percentage</td>
<td>Based on PHEV usage data</td>
</tr>
</tbody>
</table>

Modeled components of ownership costs (included - “√”, not included-“×”)

| Purchase price | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Gasoline cost  | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Electricity cost | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Vehicle salvage value | × | × | × | √ | √ | × | × | √ | √ |
| Maintenance cost | √ | × | × | √ | × | × | √ | √ | √ |
| Insurance cost  | √ | × | × | √ | × | × | √ | √ | √ |
| Tax            | √ | √ | × | √ | × | × | √ | √ | √ |
| Subsidy        | × | × | × | × | √ | × | × | × | √ |
The main contributions of this paper can be summarized as follows: (1) assess the economic viability of PHEVs based on the realistic and systemic data rather than outdated or low fidelity assumptions; (2) build a comprehensive TCO model encompassing the information of vehicle retail cost including tax and subsidies, lifetime operation cost including fueling, electricity, maintenance and insurance cost, and the expected resale value; (3) examine the determinants for PHEV owners’ economic profit in terms of vehicle distance traveled (VDT) electrically, gasoline and electricity prices, and expenditure on vehicle purchase.

The next section describes the observed driving and charging patterns of BYD Qin owners in Shanghai, China, followed by the detailed and realistic cost-effectiveness analysis in Section 3. Results and discussions are presented in Section 4. Conclusions of the study are discussed in Section 5.

2 DATA DESCRIPTION

2.1 Data Collection

This study makes use of a rich database collected from 50 PHEVs with the same model of BYD Qin from May 2015 to May 2016. These vehicles were randomly selected from the SHEVDC database. For privacy protection, the owners’ information, such as age, gender, occupation, monthly salary, household vehicle ownership etc., were not collected. The recording time for all PHEVs lasted for more than 300 days, and the average recording time for each vehicle is about 330 days. BYD Qin is a parallel plug-in hybrid vehicle equipped with a 500V 13kWh LiFePO4 battery pack and 110kW electric motor, providing an all-electric range (AER) of 70km. The range can be extended when a turbo-charged, direct-injection 1.5L starts to work (18). Vehicle terminals, such as global positioning system data loggers and instruments to monitor the electricity and fuel consumption, are installed to record the status of vehicles at the rate of two samples per minute. The data include each vehicle’s turn-on time, turn-off time, total mileage, battery state of charge, instant miles per gallon (MPG), time-stamped location (i.e., longitude and latitude), spot speed, azimuth, etc. After data cleansing and consistency checking procedures to remove invalid and erroneous data from the records, PHEVs’ users driving and charging information, which significantly affects the total cost of ownership, is extracted.

2.2 Observed Driving Patterns

The lifetime operation cost is closely related to the annual VDT. FIGURE 1 plots the distribution of the annual VDT. Overall, BYD Qin owners have higher annual VDTs than the assumptions made by (7, 8, 9), with an average value of 37,884km, and a standard deviation of 12,815km. The diversity of driving profiles for different drivers is significant, thereby providing insight into the relationship between different vehicle usage patterns and ownership costs.

Define the utility factor as the fraction of VDT powered by electricity. Variations also exist in the utility factors (FIGURE 2). The high utility factor ensures maximum savings on gasoline. To further analyze the effects of PHEV users’ driving and charging patterns, the 50 PHEVs are denoted by ID ranging from 0 to 50. The vehicle with the ID of 20 (VID 20) has the highest utility factor of 0.93, indicating a high battery utilization, while the lowest factor is 0.14 observed from VID 31. 40% of the vehicles have utility factors less than 0.5, yielding few benefits from gasoline displacement.
2.3 Observed Charging Patterns

In the ideal case, after an “overnight charge” of the battery to a high SOC (e.g. 90%), vehicles operate in charge-depleting (CD) mode. After completing all trips during the day, a low state of charge is reached, and vehicles are plugged in over the night. The electric power company in Shanghai offers reduced rates for off-peak hours (from 10:00 PM to 6:00 AM), almost half as much as that in peak hours. **FIGURE 3(a)** shows the distribution of the starting time for each charging event. Only 22.1% of the charging events occurred in off-peak hours.

We estimate the charging power based on the charging time and the increase in SOC. Almost all of the 16,467 recorded charging events are performed using a charger with an effective charging power of 3-4kW. **FIGURE 3(b)** plots the time-of-day electricity demand for charging. To generate the plot, first, the energy obtained from each charging event is estimated hour by hour, and then the time-of-day electricity demand of different events are combined into one group. Although night charging events take up a low proportion, they offer long charging time resulting in high energy obtained from the utility grid. 47.11% of the electric energy is charged in off-peak hours.

The night charge helps to reduce the electricity cost. For each vehicle, the electricity charged in the peak and off-peak hours are identified respectively (**FIGURE 4**). 22 vehicles gain more than 50% of the electrical energy in off-peak hours, while the others may not have adequate overnight charging opportunities or their working places offer daytime charging facility. Also, it may be because that they are insensitive to the electricity price. The exact causes can be further investigated if the driver information is provided. The performance of VID 20 is best, as its electrical energy obtained from the night charge accounted 89.8%. The above-mentioned driving and charging information are subsequently used in the cost-effectiveness analysis.
3 METHODOLOGY

3.1 Gross Profit

To quantify the benefits of adopting a PHEV, the gross profit $C_G (¥)$, defined as the costs for owning and operating a PHEV minus the costs of an ICEV, is estimated. If $C_G$ is negative, switching to PHEVs is not an economical choice for car owners, while if it is positive, it motivates car owners to replace ICEVs with PHEVs. The savings of vehicle purchase, energy cost, insurance cost, maintenance cost, and the benefits of resale are considered in the calculation of $C_G$. All the savings are calculated on a yearly basis. The annual savings in the future are discounted to their net present values (NPV). According to Chinese policies of vehicle scrape, private cars have to be scrapped when their mileage reaches 600,000km. Since there is little information about the service life of PHEVs, vehicles are assumed to serve their owners for 10 years as long as their cumulative mileage are less than 600,000km. Otherwise, at the end of the year when the mileage exceeds 600,000km, PHEVs must to be scrapped ahead of schedule. The gross profit is determined by:

$$C_G = C_p + \sum_{n=1}^{N} \frac{1}{(1+r)^n} (C_{E(n)} + C_{I(n)} + C_{M(n)}) + \frac{1}{(1+r)^N} C_R$$

(1)

where $C_p (¥)$ is the car-buying saving considering the subsidy and purchasing tax, $C_E (¥/year)$
is the energy-cost saving, $C_I$ (¥/year) is the insurance-cost saving, $C_M$ (¥/year) is the maintenance-cost saving, $C_R$ (¥) is the resale benefit, $r$ (%) is the discount rate, and $N$ (years) is the length of an entire vehicle life cycle.

### 3.2 Car-Buying Saving

According to the subsidy policy from both the Chinese central government and Shanghai local government, the subsidy for purchasing a BYD Qin amounts to as much as ¥ 61,500. Additionally, BYD Qin is exempt from purchase tax and qualified for a free license plate. Since the incentive of the free license is not common in the other cities, the benefit from the free license plate is not quantified in the TCO model. But its policy implication will be discussed in Section 4. Thus, the cost for purchasing PHEV is defined as its retail price minus the government subsidies, and the purchasing price of ICEV is defined as its retail price plus purchase tax.

$$C_{p}^{PHEV} = P_{r}^{PHEV} - C_s$$  \hspace{1cm} (2)$$

$$C_{p}^{ICEV} = P_{r}^{ICEV} + C_t$$  \hspace{1cm} (3)

where $C_{p}^{PHEV}$ (¥) and $C_{p}^{ICEV}$ (¥) are the car-buying cost for PHEV and ICEV respectively, $P_{r}^{PHEV}$ (¥) and $P_{r}^{ICEV}$ (¥) are the retail price for PHEV and ICEV respectively, $C_s$ (¥) is the subsidy for purchasing a PHEV in Shanghai, and $C_t$ (¥) is the purchasing tax of ICEV.

The car-buying saving of PHEV compared to ICEV is then given by:

$$C_p = P_{r}^{ICEV} - P_{r}^{PHEV} + C_t + C_s$$  \hspace{1cm} (4)

### 3.3 Energy-Cost Saving

The average VDT is denoted as $d$ (km/year). With the gasoline consumption rate $r_g$ (L/km) and the gasoline price $P_g$ (¥/L), the fuel cost of ICEVs $C_{E}^{ICEV}$ (¥/year) is written as:

$$C_{E}^{ICEV} = d \times P_g \times r_g^{ICEV}$$  \hspace{1cm} (5)

When the engine of PHEV turns on, the battery is at a “relatively constant” state-of-charge. Thus, the increased mileage in the CS mode is seen as the distance driven by gasoline. The gasoline cost of PHEVs is defined as:

$$C_{Eg}^{PHEV} = d_g \times P_g \times r_g^{PHEV}$$  \hspace{1cm} (6)

where $C_{Eg}^{PHEV}$ (¥/year) is the cost of gasoline consumption for PHEV, and $d_g$ (km/year) is the distance driven by gasoline.

We estimate electricity consumption of PHEV using the information of charging events. The energy obtained from the charging in the daytime and nighttime are identified. It is noted that the energy loss is inevitable during the charge. The charging efficiency $\eta$ is assumed as 1.3 (19). The cost of the gained energy is calculated as:

$$C_{Ee}^{PHEV} = E_{e}^{peak} \times \eta \times P_{e}^{peak} + E_{e}^{off-peak} \times \eta \times P_{e}^{off-peak}$$  \hspace{1cm} (7)

where $C_{Ee}^{PHEV}$ (¥/year) is the cost of electricity consumption for PHEV, $E_{e}^{peak}$ (kWh/year) is the
charged electricity in peak hours, $E_{e}^{\text{off-peak}}$ (kWh/year) is the charged electricity in off-peak hours, $P_{e}^{\text{peak}}$ (¥/kWh) and $P_{e}^{\text{off-peak}}$ (¥/kWh) are the peak rates and off-peak rates for electricity respectively.

The energy-cost saving is then given by:

$$C_{E} = C_{E}^{\text{ICEV}} - (C_{E}^{\text{PHEV}} + C_{E}^{\text{PHEV}})$$ (8)

### 3.4 Insurance-Cost Saving

In China, drivers must pay for a fixed-rate compulsory liability insurance every year. Besides, most of them choose to buy commercial insurance for an extra layer of protection. The third-party liability insurance, passenger liability insurance, vehicle damage insurance, and robbery and theft insurance are four major commercial insurances commonly purchased by drivers, which extend the liability, comprehensive and collision coverage. Since the retail price of the vehicle is the key factor that affects the insurance rates, two types of vehicle-price-related insurance, i.e., the vehicle damage insurance and the robbery and theft insurance are used to analyze their impacts on insurance-cost savings. The insurance-cost saving is as follows:

$$C_{I} = (P_{r}^{\text{ICEV}} - P_{r}^{\text{PHEV}}) \times (r_{1} + r_{2}) \times I_{b}$$ (9)

where $r_{1}$ ($r_{2}$) (%) is the premium rate of vehicle damage insurance (robbery and theft insurance), and $I_{b}$ (¥/veh) is the basic premium. We assume that the values of $r_{1}$, $r_{2}$ and $I_{b}$ for PHEVs are in line with those for ICEVs as no evidence has been found that PHEVs are treated differently by insurance companies.

### 3.5 Maintenance-Cost Saving

Due to lower usage of the combustion engine, PHEVs are less likely to need engine repairs and replacements compared to ICEVs, and their maintenance intervals may be spaced farther. Let $C_{m}^{\text{PHEV}}$ (¥/year) denote the annual maintenance cost of PHEV and $C_{m}^{\text{ICEV}}$ (¥/year) denote the annual maintenance cost of ICEV. The saving of maintenance cost is as follows:

$$C_{M} = C_{m}^{\text{ICEV}} - C_{m}^{\text{PHEV}}$$ (10)

### 3.6 Resale Benefits

Since data on PHEVs resale is rare, vehicles which do not have to be scraped mandatorily are assumed to serve their owners for 10 years. After that, they will be resold. In order to estimate the resale value $R_{S}$ (¥), we adopt a valuation model of the used car considering its retail price $P_{r}$ (¥) and the overall VDT $D$ (km) in an entire life cycle. Let $d_{S}$ (km) denote the scrapping kilometers limit. Vehicles are classified into five categories according to their overall VDTs, defined as $C_{q}$ ($q=1, 2, 3, 4, 5$). The total distance traveled by vehicles in Category $C_{q}$ is in the range of $[(q - 1) \times \frac{d_{S}}{5}, q \times \frac{d_{S}}{5}]$. Specifically, the annual VDTs of vehicles in Category C1 to C5 are in the range of 0 to 12,000km, 12,000 to 24,000km, 24,000 to 36,000km, 36,000 to 48,000km, and 48,000 to 60,000km, respectively. The resale value is expressed as:
\[
R_S = \begin{cases} 
\sum_{i=1}^{n-5-q+1} P_r & \text{if } D < d_S \\
0 & \text{if } D \geq d_S 
\end{cases} 
\] (11)

For example, if a car with the retail price of ¥300,000 has traveled for 450,000km after a 10-year service, it is grouped into Category C4, and its resale value is \((2+1)/15\times300,000=60,000\) yuan.

The benefit from the resale is written as:

\[
C_R = R_S^{PHEV} - R_S^{ICEV} 
\] (12)

### 3.7 Nomenclature and Parameters

The nomenclature and parameters used in this paper are summarized in **TABLE 2**.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_r^{PHEV})</td>
<td>MSRP for PHEV (¥/veh)</td>
<td>219,800(^1)</td>
</tr>
<tr>
<td>(P_r^{ICEV})</td>
<td>MSRP for ICEV (¥/veh)</td>
<td>102,900(^2)</td>
</tr>
<tr>
<td>(C_s)</td>
<td>Subsidy for purchasing PHEV in Shanghai (¥/veh)</td>
<td>61,500(^3)</td>
</tr>
<tr>
<td>(C_t)</td>
<td>Purchasing tax of ICEV (¥/veh)</td>
<td>10,290(^4)</td>
</tr>
<tr>
<td>(P_g)</td>
<td>Gasoline price (¥/L)</td>
<td>5.93(^5)</td>
</tr>
<tr>
<td>(r_g^{ICEV})</td>
<td>Gasoline consumption rate of ICEVs (L/km)</td>
<td>5.9(^6)</td>
</tr>
<tr>
<td>(r_g^{PHEV})</td>
<td>Gasoline consumption rate of PHEVs (L/km)</td>
<td>5.9(^7)</td>
</tr>
<tr>
<td>(p_e^{peak})</td>
<td>Peak rates for electricity (¥/kWh)</td>
<td>0.617(^8)</td>
</tr>
<tr>
<td>(p_e^{off-peak})</td>
<td>Off-peak rates for electricity (¥/kWh)</td>
<td>0.307(^8)</td>
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<tr>
<td>(r_1)</td>
<td>Premium rate of vehicle damage insurance (%)</td>
<td>1.088(^9)</td>
</tr>
<tr>
<td>(r_2)</td>
<td>Premium rate of the robbery and theft insurance (%)</td>
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</tr>
<tr>
<td>(I_b)</td>
<td>Basic premium (¥/veh)</td>
<td>275(^9)</td>
</tr>
<tr>
<td>(C_m^{PHEV})</td>
<td>Annual maintenance cost of PHEV (¥/year)</td>
<td>400(^10)</td>
</tr>
<tr>
<td>(C_m^{ICEV})</td>
<td>Annual maintenance cost of ICEV (¥/year)</td>
<td>650(^11)</td>
</tr>
<tr>
<td>(d_S)</td>
<td>Vehicle scrapping kilometers limit (km)</td>
<td>600,000(^12)</td>
</tr>
<tr>
<td>(rr)</td>
<td>Discount rate (%)</td>
<td>6(^(11))</td>
</tr>
</tbody>
</table>

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\(^1\) https://baike.baidu.com/item/%E6%AF%94%E4%BA%9A%E8%BF%A9/10766337?fr=aladdin
\(^2\) https://baike.baidu.com/item/%E6%AF%94%E4%BA%9A%E8%BF%A9/13678545?fr=aladdin
\(^3\) http://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
\(^4\) http://www.119.gov.cn/2013/0112/245171.htm
\(^5\) http://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
\(^6\) http://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
\(^7\) https://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
\(^8\) http://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
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\(^11\) http://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
\(^12\) http://www.shanghai.gov.cn/nw2/nw2314/nw2319/nw2404/nw32274/nw32276/u26aw39265.html
4 RESULTS AND DISCUSSIONS

4.1 Gross Profit of PHEVs

The baseline analysis is implemented based on the parameters listed in TABLE 2. The 100-kilometer gross profit, obtained by dividing the total gross profit in Eq. (1) by the distance at the unit of 100 kilometer, is used for comparison among different PHEV users. FIGURE 5 presents the costs and profits for vehicles in different categories, and vehicles in each category are ranked from highest to lowest gross profits. As shown in FIGURE 5, PHEVs can benefit from the energy-cost saving, maintenance-cost saving, and vehicle resale. However, the benefit is not enough to cover the additional expenditures on vehicle purchase and insurance. Only five vehicles have a positive gross profit. That is to say, in the present case, switching to PHEVs is not an economical choice for most drivers.
The length of service life is firstly checked. Two vehicles, VID 28 and 39, grouped into Category C0 (FIGURE 5(a)), must be scrapped as their total mileage shall exceed 600,000km after 10 years. VID 39 has the highest annual VDT of 79,979km, and its service life is supposed to be 8 years; VID 28 stops its service at the end of the 10th year. As they must be scrapped ahead of schedule, neither of them can gain from the resale benefit. The gross profit of VID 39 is positive, highlighting that it is a rational economic decision to deploy PHEV rather than ICEV. With respect to VID 28, the gross profit is negative.

No vehicle is grouped into Category C1 indicating all vehicles are with an annual VDT larger than 12,000km. The number of vehicles in Category C2 to C5 are 7, 17, 16, and 8 respectively. Since the resale value is determined by the total distance traveled during the life cycle, Category C2, which has the lowest average annual VDT, get the most benefit from the resale. Another noteworthy phenomenon is that, as the average annual VDT for each category increases, the energy-cost saving reduces. We assume that the battery capacity cannot meet travel demand for the users who have long-distance trips. Thus, the benefits of electricity usage are offset by the consumption of gasoline.

One of the vehicles in Categories C2, namely VID 20, has the highest utility factor of 0.93, with an annual distance traveled electrically of 20,322km. However, the vehicle has a negative gross profit as it rarely plugs in at night. VID 36 is ranked first in case of the 100-kilometer gross profit in Category C2 (FIGURE 5(b)). By contrast, VID 36 has a slightly less electric VDT than VID 20, i.e. 20,035 km per year, while 54.7% of its electricity consumed is charged in off-peak hours, helping it gain more savings from the energy cost.

The annual VDT of vehicles in Category C3 is in the range of 24,000 to 36,000km. Although VID 37 has the highest 100-kilometer energy-cost saving, its 100-kilometer gross profit is ranked third in Category C3 (FIGURE 5(c)). The reason for this is that VID 37 has a relatively low annual VDT of 25,252km, which increases its 100-kilometer car-buying cost and 100-kilometer insurance cost. As for VID 1, it gains the highest 100-kilometer gross profit among all the vehicles due to the long electric VDT of 26,160km per year.

Two vehicles in Category C4 have positive gross profits, and their electric VDTs are more than 31,000km per year, higher than those for any other vehicles (FIGURE 5(d)). One of the two vehicles, VID 7, is not often plugged in at night, with only 22.3% of its charges attained in off-peak hours; a high annual VDT of 42,733km helps it reduce the 100-kilometer expenditures on vehicle purchase and insurance and gain a positive gross profit. VID 43 has the lowest 100-kilometer gross profit as 81.0% of its VDT is driven by gasoline. The high annual VDT of
46,337 km makes its saving from energy cost even worse.

None of the vehicles in Category C5 has a positive gross profit (FIGURE 5(e)). Because, on the one hand, the resale benefit of Category C5 is only one-tenth of that of Category C2. On the other hand, the battery range limits the distance driven by electricity. Although vehicles in Category C5 have the highest average annual VDT, they have no advantages in electric VDT. Remarkably, PHEVs are qualified for a free license plate in Shanghai while the cost of a plate for ICEV is about ¥80,000 to 90,000, considering monthly fluctuations (20). Although the total gross profit of VID 31 is ¥ -38,670, the lowest among all the 50 PHEVs, its owner can still take advantage of the deployment of PHEVs considering the benefit from a free license plate.

4.2 Impact of Electric VDT

The 100-kilometer gross profit is found to increase linearly with electric VDT. The 100-kilometer gross profit attained by the annual electric VDT are plotted in FIGURE 6. Since vehicles in Category C0 are supposed to be scrapped, they are not included in the figure to eliminate bias. The relationship between 100-kilometer gross profit and electric VDT is described by a simple linear regression, with the R-squared value of 0.8091. The equation is written as $y = 0.38x - 10.411$, where $y$ represents the 100-kilometer gross profit (¥/100km), and $x$ represents the annual electric VDT (1,000km).

![FIGURE 6](image-url) Relationship between 100-kilometer gross profit and electric VDT.

An extreme scenario is that assuming the annual VDT of a vehicle is 56,560 km (the highest annual VDT in Category C2 to C5), and its entire mileage is driven by gasoline (i.e. $x=0$), the 10-years gross profit is ¥ -58,846 which can be covered by the benefits from a free license plate. We conclude that, if offset the 10-years gross profit by the savings from the license cost, the deployment of BYD Qin is economically feasible in Shanghai.

When $y=0$, namely, at the breakeven point $0'$ of gross profit, $x$ equals to 27.4. That is to say, to gain a positive gross profit, at least an annual distance of 27,400 km must be driven electrically during the vehicle’s life cycle. However, since the average annual electric VDT of the 50 PHEVs is 19,738 km, it is difficult for most vehicles to reach the threshold. The point $0'$ is expected to move along the X-axis as the electricity price fluctuates. Given the scenarios that both of the electricity price in peak hours and off-peak hours is increased by 20%, or decreased by 20%, 40%, and 60%, the linear regression models are generated respectively for different scenarios. The regression lines are compared side by side in FIGURE 7. A leftward shift of the breakeven point $0'$ along with the price reduction is observed. Specifically, providing a 40% reduction in electricity price, the threshold annual electric VDT is reduced to 20,596 km, which is close to the average value.
With better charging infrastructure coverage and better publicity and education, more drivers might plug in their vehicles in off-peak hours, which helps to decrease the energy cost. Another scenario is set that all charges occurred in peak hours are switched to off-peak hours, and the result of regression is presented in **FIGURE 7**. The regression line of the off-peak scenario overlaps with the 40% reduction line, with a slightly smaller threshold annual electric VDT of 20,570km.

### 4.3 Sensitivity Analysis

The sensitivity analysis of three economic parameters, namely electricity price, gasoline price, and vehicle price are performed based on the baseline scenario. With regard to the parameters of electricity price and gasoline price, they are increased or decreased by 20% each time while the other parameters are kept constant. For vehicle price, the car-buying cost $C_p^{HEV}$ is assumed decreased by 5% each time. When decreased by 25%, it is reduced to ¥118,725 considering subsidies, slightly higher than the car-buying cost of ICEVs (i.e. ¥113,190). Let $m$ be the number of vehicles with positive gross profit. The number $m$ is supposed to be affected by the changes of the three economic parameters. The number $m$ and the distributions of vehicles’ gross profits under different scenarios are presented in **FIGURE 8**.
The reductions in electricity price have the potential to promote PHEVs. As shown in FIGURE 8(a), a reduction of 40% will make half of the vehicles economically feasible. This is in line with the observation from FIGURE 7, which indicates the threshold electric VDT is close to the average value of the 50 samples providing a 40% reduction in electricity price. But in reality, the slump in electricity price seems unlikely as the electricity price for residential use is already very cheap. Off-peak charging offers a low electricity price. Supposing all peak-hours charging are switched to off-peak hours, 50% of the vehicles become feasible. With the development of fast charging infrastructure, the charging cost may go up, reducing the savings of energy cost. As the electricity price raises by 20%, the deployment of PHEVs will not be feasible in Shanghai unless in association with the incentive of a free license plate.

The increment in gasoline price contributes to vehicle feasibility more significantly (FIGURE 8(b)) – an increment of 10% in gasoline price will increase the average 100-kilometer gross profit by ¥1.75 while a reduction of 10% in electricity price will only increase the average 100-kilometer gross profit by ¥0.61. As severe fluctuations in gasoline prices have been observed in recent years, the increase in gasoline price could become a great motivator for drivers to adopt PHEVs. For example, VID 17 will gain the highest gross profit of ¥59,187 in 10 years, assuming there is a 60% increment in gasoline price. On the contrary, the gross profits decrease with the gasoline price markedly. No vehicle will have a positive gross profit if the gasoline price is reduced by 20%.

The reduction in vehicle price is expected with technological advances. As shown in FIGURE 8(c), a 10% reduction in the car-buying cost of PHEVs makes 40 vehicles feasible. When the car-buying cost drops by 25%, gross profits of all the vehicles will become positive. The contribution of cost reduction to the feasibility is examined as well – 10% reduction in car-buying cost will increase the average 100-kilometer gross profit by ¥4.69, approximately 7.6 times as much as that of electricity price, and 2.7 times as much as that of gasoline price. The government of Shanghai has gradually cut down the subsidies on NEV purchase in recent years, thereby the reduction in the car-buying cost of PHEVs is determined by the decrease in their retail prices.

5 CONCLUSIONS

This paper investigated the economic viability of replacing ICEVs by PHEVs based on the usage data collected from PHEV owners in Shanghai, China. The variations in ownership costs for PHEV drivers are examined using a comprehensive TCO model. The key findings from the results include: (1) some drivers purchase a PHEV purely because of the free license as most of their VDTs are powered by gasoline and routine overnight charging is not observed; without the incentive of free license, deploying BYD Qin is uneconomical for 90% of the users. (2) The savings from the energy cost decrease with the total distance traveled; contrarily, the distance traveled electrically is positively related with the gross profit of PHEV owners. (3) The sequence of the effectiveness of motivators to promote PHEVs is the decrease in vehicle price, an increase in gasoline price, and a discount on electricity price. For example, a 20% reduction in car-buying cost makes 96% of the PHEV deployment feasible, the feasibility is 58% for a 20% increment in gasoline price, and 26% for a 20% reduction in electricity price. (4) Off-peak charges are recommended as half of the deployment will be feasible if all charging events are performed in off-peak hours. The research can be further improved with more data, especially PHEV models with different all-electric ranges.
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AUTHOR CONTRIBUTION STATEMENT
The authors confirm contribution to the paper as follows: data collection and draft manuscript preparation: Y. Xia; study conception and design: J. Yang; analysis and interpretation of results: Z. Liu and J. Dong. All authors reviewed the results and approved the final version of the manuscript.

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