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LIFE-CYCLE COST ANALYSIS OF LOW-SPEED ELECTRIC VEHICLES USING DIFFERENT KINDS OF BATTERY TECHNOLOGIES BASED ON CHINESE MARKET

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ABSTRACT

The low-speed electric vehicle (LSEV), a product similar to the neighborhood electric vehicle in California, has experienced explosive growth in China's third- and fourth-tier cities and villages. The number of ownership has reached 4 million, but there is still no national standard regulation for it. The choice of battery type is one of the core controversies during the process of product legislation, since most LSEVs use lead-acid batteries for cost reduction nowadays, while many experts believe this would be harmful to the environment and not conducive to technical progress. This paper focuses on the battery choice issue and establishes a consumer-centric total cost of ownership model, which is composed by initial purchasing cost and operating cost, to compare the life-cycle cost of LSEVs using three different kinds of batteries including lead-acid, lithium-iron phosphate and ternary lithium-ion batteries. The results suggest that the vehicles using lead-acid batteries aren't superior to those using other types of batteries in terms of life-cycle cost, and even the superiority in initial purchasing cost will gradually weaken over time, which provides a reference for product design and regulation development.

Keywords: low-speed electric vehicle, life-cycle cost, lead-acid battery, lithium-ion battery, China

NOMENCLATURE

LSEV	Low-speed electric vehicle
VRLA	Valve-regulated Lead-acid
LFP	Lithium Iron Phosphate ($LiFePO_4$)
NCM	Nickel Cobalt Manganese
NCA	Nickel Cobalt Aluminum
LCC	Life-cycle Cost
IPC	Initial purchasing Cost
OC	Operating Cost

1. INTRODUCTION

The Chinese new energy vehicle (NEV) market has achieved rapid development in the past few years under the implementation of a package of incentive programs and policies. In 2018, China's NEV sales reached 1.26 million, with battery electric vehicle(BEV) sales reaching over 0.98 million and constituting 78.3% of all NEVs [1]. At the same time, a special type of small electric vehicles with four wheels, a maximum speed of 40-70km/h and a relatively low electric driving range develop dramatically without subsidies. Shandong province contributes more than 60% LSEV sales, and the sales volume in 2017 was about 0.76 million, with the compound annual growth rate reaching 55% from 2012 to 2017. Although the sales decreased in 2018 to 0.70 million due to some regulatory factors, this kind of vehicles of which current stock is about 4 million units in China really worth studying [2-3].

The LSEV sector is still in the grey zone of regulation despite large sales and stocks, resulting in the unordered market competition and problems in traffic safety [4-5]. Legislation to regulate and standardize LSEVs has been discussed since 2016, but the standard hasn't been released till yet because of so many disputes especially on battery types [6]. The management of LSEVs has been tightened from 2018 [7], obviously affecting the production and sales of LSEVs in the short term, but it will lead to the improvement of product quality and safety in the long run.

Most research on LSEV batteries focuses on comparing the regulations between different countries to propose possible management measures for China, with few quantitative results indicating how different kinds of batteries influence the products [8]. In order to fill the gap and provide a digital reference for battery selection disputes, this paper establishes a framework to quantitatively analyze the life-cycle cost of ownership of

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LSEVs, considering the cost is the key factor affecting the attractiveness of the vehicles for price-sensitive consumers.

2. METHODOLOGY AND DATA

As Fig.1 shows, the Life-cycle cost(LCC) includes initial purchase cost(IPC) which is composed of battery system cost(BSC) and other components/glider cost(GC), and operating cost(OC) containing energy consumption cost(ECC) and battery replacement cost(BRC).

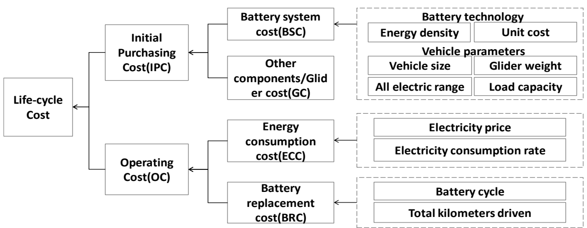

Fig 1 Framework of this study

2.1 Vehicle parameters and lifespan

In order to analyze the LCC of LSEVs, the value or range of LSEVs' parameters involved in the calculating process must be defined [9]. Nearly 150 models of 10 mainstream brands are chosen considering the accuracy and representativeness of data, for there are no national standards for LSEVs. These manufacturers chosen have relatively complete industrial chains, and they provide relatively complete product parameters including model size, driving range (here means cruising range at constant speed), and battery-related parameters. The detailed definition of typical LSEV whose glider weight is in the range of 500 to 800kg is listed in Table 1.

Table 1 Definition of value or range of vehicle parameters

Symbol	Detailed meaning	Value or range	Model
l	The length of vehicle/mm	2800~3800	3300
w	the width of vehicle/mm	1420~1690	1524
h	the height of vehicle/mm	1510~1520	1513
m_c	the curb weight/kg	600~1100	820
n_{man}	the number of humans	2~5	4
m_l	the maximum load weight/kg	200~400	300
AER	All electric range/km	50~150	100
v_{max}	the maximum speed/km/h	35~70	50
η_m	the transmission efficiency	0.8~0.9	0.85
C_d	the air resistance coefficient	0.25~0.40	0.40
g	acceleration of gravity/m^2	9.8	9.8
ρ	the density of air/kg/m^3	1.2258	1.2258
f	the rolling resistance coefficient	0.015	0.015

Since the discussion in this paper is based on high-quality, brand-strength products and future policy requirements, the lifespan of light-duty vehicles will be regarded as the major reference, so the lifespan of the LSEVs is assumed to be eight years with a total mileage of 80,000km [10]. Because the proportion of LSEV users whose daily mileage traveled is less than 30km (the annual mileage is about 11,000km) is 86% [11], the average annual mileage of LSEVs used in this study is 10,000km.

2.2 Battery energy density and cost

The VRLA batteries have been widely used in LSEVs mainly due to the lower cost. However, with the rapid performance improvement and cost reduction of the lithium-ion batteries, some products began to use LFP and NCA/NCM batteries. According to the government's plan, the energy density will be improved to 260wh/kg, 280wh/kg, 350wh/kg and the industry-wide unit cost of a battery pack will be reduced to 1￥/Wh, 0.9￥/Wh, 0.8￥/Wh in 2020, 2025 and 2030 respectively [12-13]. The estimation and prediction of the energy density and cost of VRLA and mainstream Li-ion battery packs are shown in Table 2 and Table 3.

Table 2 Battery pack density of different batteries

	Energy Density (Wh/kg)				
	2018	2019	2020	2025	2030
VRLA	40	40	40	40	40
LFP	115	120	125	131	138
NCM/NCA	169	209	260	280	350

Table 3 Battery unit cost of different batteries

	Unit cost (yuan/Wh)				
	2018	2019	2020	2025	2030
VRLA	0.800	0.800	0.800	0.800	0.800
LFP	0.948	0.842	0.784	0.750	0.719
NCM/NCA	1.480	1.220	1.000	0.900	0.800

2.3 Initial purchase cost

The battery purchase cost is equal to the product of the vehicle battery capacity and the unit cost, as Eq. (1) shows.

$$BSC = R \cdot \tau \cdot 1000 \qquad (1)$$

Where R denotes the vehicle battery capacity (kWh), τ denotes the unit cost of the battery pack (￥/Wh).

Since there is no standard test condition for LSEVs, the battery capacity is obtained by calculating the total energy consumed at full load. According to vehicle dynamics, the relationship is stated as follows [2-5].

$$F_d = mgf + \frac{1}{2} C_d A \rho u^2 \qquad (2)$$

$$m = m_g + m_b + m_l \qquad (3)$$

$$m_b = \frac{R}{\gamma} \cdot 1000 \qquad (4)$$

$$R = AER \cdot F_d / (3600 \eta_m) \qquad (5)$$

Where F_d denotes vehicle driving resistance (*N*), A denotes the frontal area of the vehicle, *u* denotes average driving speed (m/s), here *u* is 35km/h (9.72m/s) according to most test methods in the market. m_g, m_b denotes glider weight (kg), battery system weight (kg) respectively, γ denotes the energy density of the battery (Wh/kg).

Based on the manufacturer's suggested retail price of LSEVs in the Chinese market, the relationship between the glider cost and glider weight is linearly fitted indicated in Eq. (6).

$$GC = \left(0.0028 \cdot m_g + 1.284\right) * 10000 \tag{6}$$

2.4 Operating cost

If the battery life is exhausted during the life of the LSEV, the battery needs to be replaced, resulting in battery replacement cost. The value of the cost can be derived through equations [7-9].

$$BRC = \begin{cases} \sum_{i=1}^{K} \frac{BSC_i}{(1+r)^{i \cdot \theta}} & (K \geq 1) \\ 0 & (K = 0) \end{cases} \tag{7}$$

$$K = [VL/(\varepsilon \cdot AER)] \tag{8}$$

$$\theta = (\varepsilon \cdot AER)/AMT \tag{9}$$

Where BSC_i denotes the battery system cost (￥) of the *i-th* battery replacement, *r* denotes the annual discount rate used in order to compare all costs on an equal basis, here *r* is 1.5% estimated based on China's one-year certificate of deposit rate currently. *VL* denotes the vehicle lifespan (km), *AMT* denotes annual mileage traveled (km), ε denotes the battery cycle number. The cycle times of VRLA, LFP and NCM/NCA is 400, 2500 and 1500 respectively in this study [14].

The energy consumption cost means the electricity fee paid by customers for the LSEV's use, which can be calculated by equation [10-12].

$$ECC = \sum_{i=1}^{[N]} \frac{ECC_i}{(1+r)^i} + (N - [N]) \cdot \frac{ECC_{[N]+1}}{(1+r)^{[N]+1}} \tag{10}$$

$$\mathrm{N} = VL/AMT \tag{11}$$

$$ECC_i = p \cdot \alpha \cdot \frac{AMT}{100} \tag{12}$$

Where ECC_i denotes the energy consumption cost (￥) of the i-th year, α denotes the electricity consumption rate of LSEVs (kWh/100km), p denotes electricity price (￥/kWh), the price for residential electricity here is estimated to be 0.548￥/kWh.

3. RESULTS AND DISCUSSIONS

The total cost, operating cost and initial purchasing cost of LSEVs are presented in Fig.2, of which the first row shows the life-cycle cost, battery replacement cost and energy consumption cost respectively, and the second row specifically shows the initial purchasing cost with changing glider weights, AERs and time considering the importance of IPC for customers.

From the perspective of the total cost, LSEV using the LFP battery is the lowest, while that using VRLA battery is the lowest. The change of battery replacement times results in the image showing a fold line shape. With certain vehicle lifespan and battery cycle times, increased driving range reduces the frequency of charging, which extends battery life, but also increases acquisition costs. In the range of 50~150km AER and 500~800kg glider weight, for LSEVs using VRLA batteries, the driving range of 50km, 70km and 100km is the breakpoint, and the battery needs to be replaced once when AER is less than 53km even for vehicles using NCM/NCA. The LSEVs using LFP don't need to replace the battery because of the high battery life.

In terms of operating cost, because of the short cycle times of VRLA batteries, the number of replacements is high, resulting in higher BRC. Since the ternary lithium battery has the highest energy density, the battery

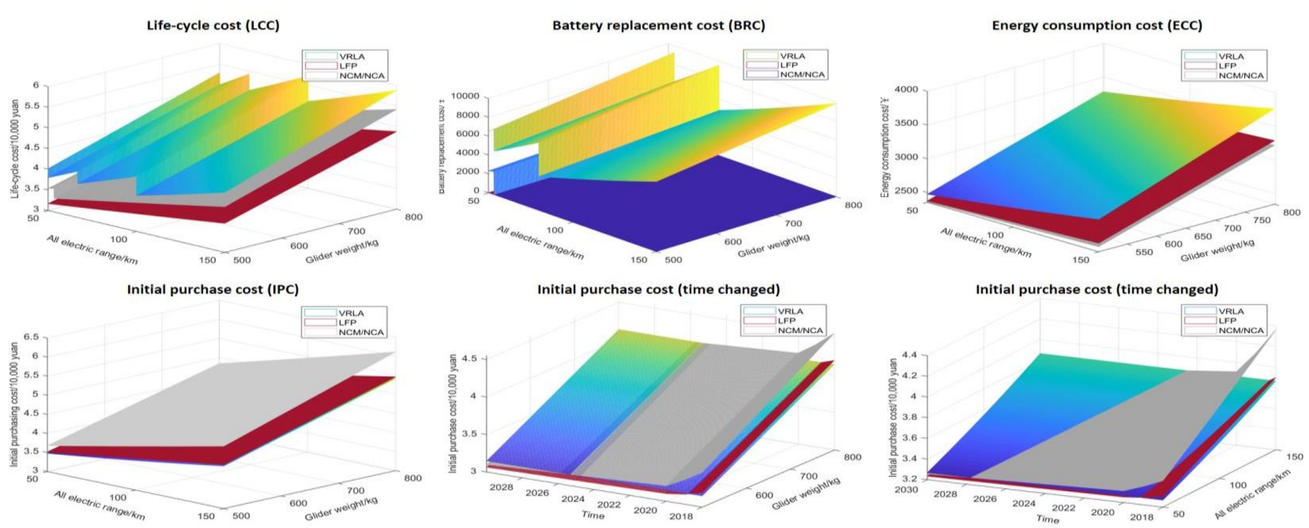

Fig 2 Life-cycle cost and different parts of it for different battery technologies, electric ranges and glider weights

capacity required to achieve the same driving range is the smallest, so the electricity consumption rate is the lowest, the power cost is the smallest and the slope of growth is also the minimal.

The second row of fig.1 shows that the IPC of LSEV using lead-acid batteries is still the lowest nowadays. Due to the rapid improvement in battery performance and the cost reduction, the IPC of LSEVs using LFP or ternary lithium-ion batteries will change significantly over time. The LSEVs using VRLA batteries will lose its advantage in terms of IPC from around 2020. Due to low travel speed of vehicles, the impact of the battery performance gap isn't obvious when the AER is short. It can also be concluded that when the driving range is 50km, the IPC of LSEVs using ternary lithium-ion batteries is lower than that of using lead-acid battery by 2026, and at 150km driving range, it can be realized around 2024.

4. CONCLUSIONS

With the technical development and cost reduction of batteries, the choice of LSEV battery types and future development direction will be clearer.

The study suggests that although the IPC of LSEVs using VRLA batteries is the lowest at this stage, it will lose advantage soon after 2020. From the perspective of LCC, even in current situation, the LCC using LFP batteries is lower than that using VRLA batteries, unlike most traditional researches that the cost of LSEVs using lithium-ion batteries will be much higher. The results show more possibilities for LSEVs' battery type choices. Therefore, it should be considered mainly from the perspectives of environment protection and technology progress during legislative process for LSEV batteries, and the vehicle companies should also fully consider the conclusion when developing LSEV products. Besides, the driving range and glider weight are also important factors for LCC. Selecting the appropriate driving range considering the integration of vehicle life, battery life and using intensity of LSEVs will not only beneficial to IPC, but also minimize battery replacement times. Enterprises can also apply lightweight technologies to reduce vehicle energy consumption rate. In sum, the policy should stimulate enterprises to pay more attention to improving the technical level and product quality of the vehicle, thus making LSEVs become environment-friendly and high-quality products to carry the responsibility of car-sharing tools in the future urban transportation system.

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