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Integrated Sustainability Assessment of Electric Bus Adoption: A Comprehensive Model for Ecological, Economic, and Operational Impact

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Abstract. The spread of electric stations in cities around the world is an important step towards sustainable urban transportation. In Task 1,We developed the FE-VC model to determine carbon emission indicators based on the BWM approach, and demonstrated the ecological consequences over the life cycle through quantitative models. In the quantitative calculation of urban data, compared with diesel buses, the carbon emission reduction rate of pure electric buses is 28.68%, mainly from the fuel cycle, in which the carbon emission reduction rate of the fuel cycle stage is as high as 40.11%, and it takes about 3.5 years to achieve the relative carbon emission reduction. In Task 2, we construct an economic impact consequence model based on the time value of capital with the theory of time value of money as the core, consider the full life cycle of acquisition, operation and vehicle maintenance, quantify and visualize the impact mechanism of electric buses on the economy, and provide a method to understand the economic impact for metropolitan areas. For task 3, based on the optimal enterprise operating cost and the optimized economic impact model, we construct the initial replacement model of the electric bus. The initial replacement model was optimized by simplifying the social cost of carbon emission, and an electric bus replacement model based on the optimal enterprise operating cost was obtained. In city-specific applications, we find that vehicle choice has a significant impact on fleet replacement plans and operating costs, and that using multiple vehicles can significantly reduce operating costs as electrification rates increase.

Keywords: Carbon emissions; Dual-layer life cycle; BWM; FE-VC; Time value of money; Optimal enterprise operating cost.

1. Introduction

1.1 Problem background

The global adoption of electric stations is crucial for sustainable urban transportation amidst rising concerns over air pollution and climate change. Governments are incentivizing electric vehicle usage, with China leading in production and adoption. Despite challenges like high infrastructure costs and charging limitations, electric transportation offers long-term cost savings and contributes to a greener urban future.

Invited by transportation officials, we aim to develop an ecological model to assess the transition to all-electric buses. Considering external funding, we've built a financial model and crafted a 10-year roadmap for the city's electric bus fleet. This detailed plan aligns with our goal of achieving sustainable urban transportation.

Figure 1 Schematic diagram of the three-dimensional model of electric bus charging

1.2 Restatement of the problem

Taking into account the background information and constraints identified in the prob- lem statement, we need to address the following questions:

- Question 1: Develop an ecological model for transitioning to all-electric buses in a metropolitan area with a population of at least 500,000.
- Question 2: Create a financial impact model considering external funding covering up to 50% of transition costs; apply it to the city in Question 1 for evaluation.
- Question 3: Build an electric bus replacement model based on the ecological and financial models; apply it to cities in Questions 1 and 2 to develop a 10-year roadmap for urban transportation renewal. Extend the model to two additional metropolitan areas.

1.3 Our work

Our team, after literature review [1], identified carbon emissions as the key factor for ecological consequences. We proposed dual life cycles, analyzed emissions at each stage, determined weights through BWM, and constructed a quantitative ecological model. To address cost concerns, we employed the NPV theory and considered the entire life cycle for acquisition, operation, and maintenance, creating an economic impact model. Integrating ecological and economic models, we enhanced coupling and built an electric bus replacement model based on optimal operating costs, aiding transportation planning for a 10-year transition.

2. Assumptions

It is assumed that some non-core processes in the carbon emission quantification model, such as vehicle transportation and vehicle operation and maintenance, except for batteries and tires, have zero carbon emissions.

It is assumed that the average level data of the petroleum products processing industry is used to replace the diesel processing data and the national average power transmission loss rate is used.

It is assumed that the operation and maintenance costs of charging piles are extremely small, and there is no need to consider the cost of charging piles in operating conditions.

Assuming potential funding, 50% of transition costs can be covered.

It is assumed that there are no hybrid buses currently in operation.

It is assumed that the operating expenses incurred during the use phase of the charging pile are extremely small and can be ignored.

3. Ecological Consequence Model of Electric Buses

We developed an electric bus ecological model focusing on urban ecological consequences during a full transition to electric buses. Recognizing carbon emissions as the central factor impacting climate change and air quality, we adapted the model to emphasize carbon emissions. Using a two-layer life cycle design, we analyzed fuel and vehicle cycles, determined weights through BWM, and formed the comprehensive FE-VC model. This model facilitates primary and secondary analyses of various ecological aspects, enabling weighted comprehensive analysis. Applied to specific cities, it quantitatively analyzes data, enhancing public understanding of ecological consequences.

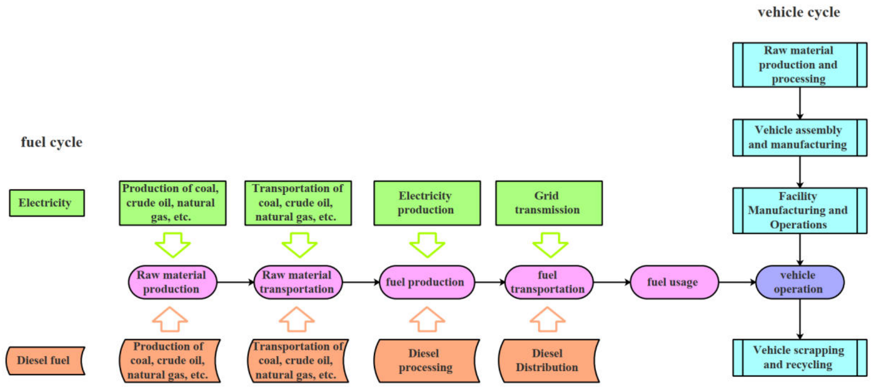

Figure 2 Double-decker bus life cycle flow chart

3.1 Impact factor analysis

3.1.1 Analysis of the ecological impact of carbon emissions

Since modern times, rapid economic development and a soaring global population have led to increased human activities, causing significant damage to green spaces. This has resulted in a sharp rise in air carbon dioxide levels and heightened air pollution from toxic gases. The excessive release of greenhouse gases and air pollutants has led to ecological deterioration and triggered global warming [2,3]. In 2018, an IPCC data report indicated a 1°C increase in the global average surface temperature compared to pre-industrial levels. If the current rate continues, a 1.5°C warming is anticipated within two decades from 2030, necessitating urgent policy reformulation and implementation worldwide to reduce carbon emissions [4]. The report emphasizes the urgency, stating that a 2°C temperature rise would surpass expectations and that achieving net-zero emissions globally by 2050 is crucial to mitigating climate change risks and stabilizing the average temperature at the international target level [5].

The transportation sector, heavily reliant on energy, accounted for 29% of global energy consumption in 2015, with 95.9% from fuels, 3.1% from renewable energy, and only 1% from non-renewable energy electricity [6]. Road transport emissions, including passenger and freight, contribute 60% and 40%, respectively [7].

3.1.2 Analysis of influencing factors of carbon emission model

(1) Carbon emissions in fuel production and transportation result from energy-intensive processes, including raw material extraction and processing [8].
(2) Carbon emissions from bus raw material production involve energy consumption and chemical reactions in the manufacturing process of metals, plastics, rubber, and other materials [8].
(3) During bus operation, carbon emissions mainly originate from fuel combustion. The fuel type is crucial, with traditional diesel buses emitting more carbon than alternative energy or electric buses, which significantly reduce emissions [9].
(4) Carbon emissions in the construction and maintenance stages of bus operation facilities arise from daily energy consumption, maintenance activities, and facility upkeep. Bus stops, lighting, air conditioning systems, and mechanical equipment usage contribute to carbon emissions [10].

3.2 Symbols

3.2.1 Determination of indicator weight based on BWM

According to the basic principles of BWM [11] and combined with uncertainty theory, the specific steps for calculating indicator weights of the uncertain BWM model are given:

Step 1: Specify the level of importance for the comparison situation.

There are m levels of importance in comparisons between specified indicators. Expressed as $P=(P_1,P_2,\ldots,P_m)$. Taking into account the uncertainty of the decision-maker's subjective consciousness and the uncertainty of the evaluation information itself in the process of determining the importance level, will $P_k(k= 1, 2,.., m)$ regarded as an uncertain variable, And represented by . Ψ

Step 2: Establish an evaluation indicator set.

Suppose there are n evaluation indicators in total, then the evaluation indicator set $C=C(C_1,C_2,\cdots,C_n)$.

Step 3: Select the best indicator and the worst indicator.

The decision-maker selects the best index C_b and the worst index C_w from the constructed evaluation index set based on his or her own experience.

Step 4: Based on the optimal index, determine the uncertain comparison vector.

Using C_b as a reference, make pairwise comparisons with all other indicators to construct a comparison vector $A_b = (a_{b1}, a_{b2},\ldots,a_{bm})$ between the optimal indicator and other in-dicators. Where a_{bj} represents the importance level C_b compared to the j indicator $C_j(j=1,2,\ldots,n)$. Then isexpressed as:

$$a_{bj}=\xi_k \tag{1}$$

Formula (l) expresses that C_b compared with C_j, the importance level of C_b is $\xi_k(k=1,2,\cdots,m)$.

Step 5: Based on the worst indicator, determine the uncertain comparison vector.

Using C_w as a reference, compare all other indicators with and construct a comparison vector between the remaining indicators and the worst indicator.

Step 6: Construct an uncertain optimal and worst model, calculate the weight of each indicator, and construct the following model from the perspective of expectations:

$$\min \max\{|E(a_{bj})\omega_j-\omega_b|,|E(a_{jW})w_W-\omega_j|\} \tag{2}$$

$$s.t.\begin{Bmatrix} \sum_j \omega_j=1 \\ w_j\geqslant 0,\ j=1,\ 2,\cdots,n \end{Bmatrix} \tag{3}$$

Using the BWM method, the final weights are as follows:

Table 2 Weight of carbon emissions at each stage

Primary index	Index	Weight
carbon emission	fuel production transport	0.083
	Raw material production and processing	0.092
	running phase	0.721
	Operational facility construction and maintenance	0.104

Our team established an ecological consequence evaluation model, employing the BWM method for a detailed analysis of replacing diesel buses with electric ones. This model elucidates the reduction in carbon emissions at each stage, aiding public comprehension of the ecological impact. In Step 3, the decision-maker selects the best and worst indicators from the evaluated set based on their experience with n total indicators.

3.2.2 Construction of carbon emission quantification model

The carbon emission quantification model takes the life cycle as the underlying frame- work and uses the emission coefficient method to calculate the carbon emissions of diesel buses and electric buses at each stage.

(1) Calculation of life cycle carbon emissions of fuel production and transportation:

$$\xi_T = \gamma_e \times \varphi \times E \tag{4}$$

Among them, ξ_T represents the carbon emissions during fuel production and transportation, γ_e represents the fuel carbon emission coefficient, φ represents the energy efficiency, E represents the energy consumption structure proportion.

(2) Calculation of carbon emissions from bus raw material production and processing:

$$\xi_p = \sum_{i=1}^{n} \frac{\Gamma_i \times \gamma_i}{H} \tag{5}$$

Among them, ξ_p represents the carbon emissions from bus raw material production and processing, Γ_i represents the material production quality, γ_i represents the material carbon emission coefficient, H represents the material production yield.

(3) Calculation of carbon emissions during bus operation:

$$\xi_u = \frac{M \times N \times L}{\theta} \tag{6}$$

Among them, ξ_u represents the carbon emissions of the bus during operation, M represents the fuel/electricity consumption of the bus per 100 kilometers, N represents the carbon emissions per unit of electricity or diesel, L represents the mileage of the bus, and θ represents the charging efficiency/fuel transmission efficiency.

(4) Calculation of carbon emissions during the construction and maintenance stages of bus operation facilities:

$$\xi_h = (\xi_c + \xi_m) \times L \tag{7}$$

Among them, ζ_h represents the carbon emissions during the construction and maintenance stage of bus operation facilities, ζ_e represents the carbon emission coefficient during the construction stage of bus operation facilities, and ζ_m represents the carbon emission coefficient during the maintenance stage of bus operation facilities.

3.3 Specific application of the ecological consequences model of electric buses

We chose Hangzhou (with a current resident population of 12.24 million) as the testing metropolis and applied the model to calculate the city's carbon emissions using data collected as shown in Table 3.

Original data source: Hangzhou Data Open Platform

Table 3 Carbon emissions of diesel buses and electric buses

Bus category	Raw material production and processing		Assembly manufacturing	Running phase		Facility maintenance		sum
	vehicle	Battery	Assembly manufacturing	Fuel upstream	fuel downstream	operations	maintain	
diesel bus	112.693	0	1.362	193.256	1230.562	1.663	52.365	1591.901
electrician bus	126.845	79.235	1.362	852.365	0	5.326	70.236	1135.369

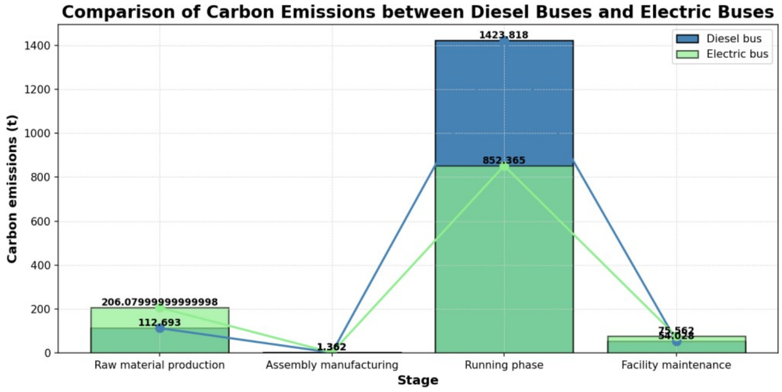

Figure 3 Comparison of carbon emissions at various stages between diesel buses and pure electric buses in Hangzhou

The carbon emission reduction rate of pure electric buses in Hangzhou compared to diesel buses is 28.68%, primarily due to a 40.11% reduction in carbon emissions during the fuel cycle stage, validating the accuracy of our evaluation model. Presently, electric buses in operation in Hangzhou have reduced carbon emissions by 689,170 tons during their lifecycle, with a transition period of approximately 3.5 years required for full conversion from oil to electricity to realize relative carbon emission reductions.

4. NPV-based financial impact model of electric buses

4.1 Determination of indicator parameters of financial impact model

4.1.1Acquisition cost analysis based on potential external funding

By analyzing key core components' current prices, the average ex-factory cost of various vehicle types, including diesel bus A1 and electric bus B2, is calculated based on simulated parameters queried from data.

Table 4 Specific parameters of two types of buses

parameter	A1	B2
Displacement/mL	8500	0
Power/kw	189	110
Length/m	11.98	11.96
Battery charge/(A·h)	0	62

Since the support policies for electric buses in various regions and countries are different, we investigated the policies of many places.

(1) China
Hybrid buses over 10m may get 200,000+ yuan subsidy; pure electric buses meeting power criteria could receive 500,000 yuan promotion subsidy. Hybrid bus subsidy is 250,000 yuan, pure electric bus subsidy is 500,000 yuan; no policy support for ordinary diesel buses.

(2) USA
The U.S. federal government offers up to $2 million in support for electric bus purchases through its low- or zero-emission vehicle program, and certain states, like California, provide additional subsidies, such as car purchase subsidies of up to $300,000.

(3) Germany
Germany's electric bus subsidy program offers up to 80% of vehicle purchase subsidies, reaching hundreds of thousands of yuan. Certain German cities, like Berlin, provide charging infrastructure construction subsidies of up to 300,000 euros, as part of the government's encouragement for electric bus adoption.

These potential external funds can cover 50% of the bridge funding.

4.1.2 Maintenance costs

Bus maintenance costs in Hangzhou vary with vehicle type. For diesel buses, costs start at 6,000 yuan in the first year, rising to 12,000 yuan in the second year, with a subsequent annual increase of 2,000 yuan. Electric buses incur higher costs due to electronic control systems and drive motors, representing 10% and 12.5% of total costs, respectively. Battery replacements are needed in the 3rd and 5th years, with the first replacement costing 600,000 yuan and the second 400,000 yuan.

Table5 Repair and maintenance cost for 2 types of bus (unit: × 10^4 yuan)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
A1	0.6	1.2	1.4	1.6	1.8	2.0	2.2	2.4
B2	2.6	3.2	63.4	3.6	3.8	44.0	4.2	4.4

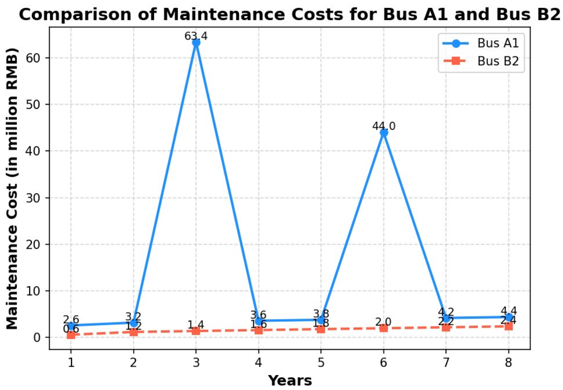

Figure 4 Estimated repair and maintenance costs for two types of vehicles

4.1.3 Energy consumption cost

Ongoing bus operation investment primarily involves energy consumption costs. For the selected diesel bus, this cost is calculated based on the unit price of diesel and fuel consumption per 100 kilometers, while the electric bus relies on the real-time unit price of electricity for its energy consumption cost per 100 kilometers.

4.2 Construction of financial impact model of electric buses based on NPV

This model is based on NPV as the theoretical basis, and the time value of money theory[12](NPV) is the basis of project economic analysis. Economic analysis in project evaluation necessitates accounting for the time value of funds, crucial for assessing multiple solutions' viability. The life cycle cost model for buses, encompassing acquisition, maintenance, and energy consumption costs, is updated using the time value of money theory to enhance economic analysis accuracy.

Table 6 Financial impact factors

Impact factor	Make up children	input characteristics
acquisition cost	Factory cost	One-time investment
	purchase tax	One-time investment
	Government subsidies	One-time investment
Maintenance cost	Maintenance fee	Invest multiple times every year
	Recover residual value	Disposable recycling
energy cost	Consumption cost	Invest multiple times every year

Construct a static financial impact function based on the table contents: .

$$X = X_p + X_t + X_r + X_s + \sum_{n=0}^{N}(X_m + X_n) \tag{8}$$

In the formula, N is the life cycle of the bus; X_p is the factory cost; X_t is the purchase tax; X_r is the government subsidy; X_s is the scrap recovery residual value; X_m is the maintenance fee in the nth year; X_n is the fuel consumption fee in the nth year. Due to gov- ernment subsidies and recycling The residual value is the amount of money flowing in, so it is actually a negative number when calculated.

The dynamic investment cost analysis of a bus project, based on net present value, requires considering the time value of funds for investment items beyond the project base year. The impact is positively related to the investment item and negatively correlated with the discount rate. The dynamic cost model during the bus life cycle is then established.

$$X = \frac{X_p}{(1+i)^{N(p)}} + \frac{X_t}{(1+i)^{N(t)}} + \frac{X_r}{(1+i)^{N(r)}} + \frac{X_s}{(1+i)^{N(s)}} + \sum_{n=0}^{N}\frac{(X_m + X_n)}{(1+i)^n} \tag{9}$$

5. Electric bus replacement model based on optimal enterprise op- erating costs

5.1 etermination of electric bus replacement model indicators

The model focuses on transitioning from old fuel/hybrid buses to electric ones to increase electrification rates in bus fleets. It considers life cycle and fleet management costs, including charging infrastructure. The model also includes social carbon emission costs and a simplified ecological impact model, aligning with a 10-year transportation sector roadmap. This is integrated into an optimized economic impact model for electric bus replacement, targeting optimal operational costs. The model is applied in three metropolitan areas, starting with Hangzhou. Data from Hangzhou includes annual mileage, line length, and operations of fuel buses, with a retirement age of 10-13 years. Initial analysis involves assessing the number and age distribution of fuel vehicles.

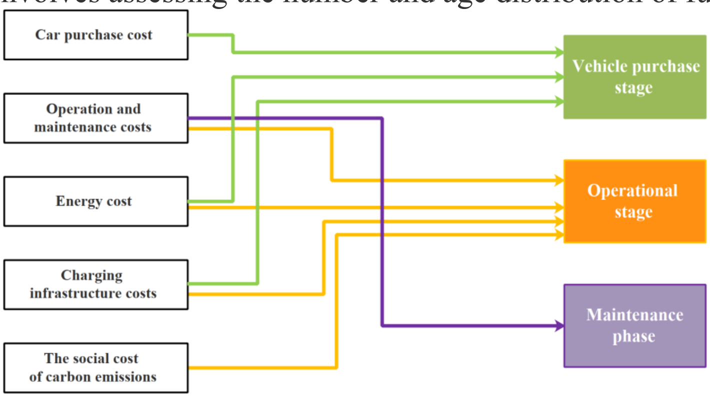

Figure 7 Principle diagram of electric bus replacement model based on optimal enterprise operating costs

5.2 Construction of electric bus replacement model based on optimal en- terprise operating costs

(1) Bus purchase cost

$$\min \ \Phi = \sum_{t=0}^{5}(\Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 + \Phi_5) \tag{10}$$

(2) Operation and maintenance costs

$$\Phi_1 = \sum_{n=1}^{n} F_{tn}(X_p + X_t - X_r) \tag{11}$$

$$\Phi_2 = \sum_{n=1}^{N}\sum_{i=0}^{I} E_{tni} f_{ni} p_{tn} \tag{12}$$

(3) Energy consumption cost

$$\Phi_3 = \sum_{n=1}^{N}\sum_{i=0}^{I} E_{tni} s_n p_{tn} \tag{13}$$

(4) Charging infrastructure cost

$$\Phi_4 = \sum_{n=1}^{N} Y_{tn} e_n \tag{14}$$

(5) Social cost of carbon emissions We simplified the ecological consequences model of electric buses we constructed into the social cost of carbon emissions and incorporated it into the electric bus replacement model.

$$\Phi_5 = \sum_{n=1}^{N}\sum_{i=1}^{I} \omega E_{tni} W_{ni} p_{tn} \tag{15}$$

5.3 Specific application of the model

By applying our model to Hangzhou, Qingdao and Mexico City, we found that initial priorities in the switch to electric buses focus on purchasing larger buses to mitigate transport issues and personnel costs, thus reducing total energy cost per unit distance. As the plan progresses, the emphasis shifts from energy cost to vehicle purchase costs. To reduce overall cost, it's recommended to buy less expensive, smaller buses later, like B3 type, while using B2 type (medium-sized electric bus) for mid-term transition. This approach ensures a stable, efficient and cost-effective full transition to electric buses.

6. Model evaluation and further discussion

6.1 Model advantages

(1) Double-layer life cycle: The double-layer life cycle of buses is innovatively proposed to reduce the coupling between the fuel life cycle and the vehicle life cycle, making it easier to build quantitative models.

(2) Graphical representation: Try to display the model principles in a graphic way to facilitate readers to understand the model structure.

(3) Model construction: Based on reality, the influencing factors of the model should be more perfected to make the model more suitable for real-life applications.

6.2 Insufficient models

(1) Assumptions: When making assumptions, the rationality of some bus assumptions cannot be fully verified and explained.

(2) Estimation: Due to the complexity of the model, we estimated some parameters in the model, which produced certain errors in the results.

7. Conclusion

In response to question 1, we developed a set of ecological consequence models. We first clarified that carbon emissions are the core factor affecting air quality and climate change. Regarding carbon emissions, we constructed a two-layer cycle of fuel and vehicles based on the idea of life cycle. The ecological consequences model uses the BWM method to determine the proportion of carbon emissions at each stage, and then constructs a quantitative model to concrete the abstract data and further help the public understand the ecological con- sequences of electric vehicles and buses. The stages serve as an impact on ecology and cli- mate. In the areas with the greatest impact, replacing all electric buses with electric buses can effectively reduce carbon emissions.

In response to question 2, we used the time value of money theory (NPV) as the core theory and the entire life cycle of acquisition, operation, and vehicle maintenance as the core influencing factors to construct an economic impact consequence model based on the time value of capital. We found that if the transportation department imagines To replace all fuel buses with electric buses, how to reduce the purchase and maintenance costs of electric buses has become the most important issue that the department should consider. At this time, poten- tial funds, such as government subsidies or corporate investments, can cover 50 % of transi- tion funds can help the transportation department better solve transition problems.

In response to question 3, we integrated the previously constructed ecological conse- quences model and the economic impact consequence model, increased the coupling between the two, and constructed an electric bus replacement model based on optimal corporate oper- ating costs to help the transportation department plan electric buses. Bus replacement routes in 10 years. Through application in actual cities, we suggest that the replacement routes of electric buses give priority to purchasing larger buses in the first few years to alleviate as much as possible the transportation problems caused by the replacement of vehicles and re- duce operational costs. costs, and can reduce the total cost of energy consumption per unit mileage. In the later stages of planning, the impact of the total energy consumption cost is reduced, while the impact of car purchase costs becomes greater. At this time, it is recom- mended that the transportation department choose to purchase smaller cars with lower prices to Reduce overall planning costs and ultimately achieve a smooth and efficient transition to fully electric buses.

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