Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 11, No. 2, 2024

Integrated Optimization Study of Electric Bus Fleet Transformation

-- Based on LCA, LCC and Multi-objective Planning

Gaobo Wang [1], Yi Zhao [2], Yifan Pan [3] and Tingyang Shi [4]

[1] Cardiff Sixth Form College, Cardiff, CF24 0AA, UK
[2] Hangzhou Foreign Language School CAL Centre, Hangzhou Zhejiang, 310000, China
[3] Hangzhou Dipond School of Art and Science, Hangzhou Zhejiang, 311100, China
[4] Hangzhou New Channel, Hangzhou Zhejiang, 310015, China

Abstract: With the increasing social demand for sustainable and environmentally friendly transportation, the transformation of public transportation systems has become an important issue. In this paper, three mathematical models are developed to synthesize the ecological consequences, financial models and transition scenarios in the transition from diesel to electric bus fleet. In Problem 1, this paper adopts the Life Cycle Assessment (LCA) method to examine the full life cycle energy consumption of the product. The model comprehensively considers the main raw material production stage, vehicle assembly and distribution stage, vehicle driving stage and vehicle scrapping and dismantling stage, as well as the production stage of all types of energy added to the vehicle driving stage, i.e., the production stage of fuels and electricity, and finally applies Gabi, the life cycle evaluation software developed by PE Germany, to carry out the evaluation of the life cycle energy consumption and greenhouse gas emissions. Finally, the energy-saving potential of pure electric buses reaches 12.69%, and the GHG emission reduction potential reaches 6.05%. The results are applied to the bus fleet in Beijing, and it is calculated that the replacement of the bus fleet with pure electric buses can save 21.87% of energy and bring about a total GHG emission reduction of 60,700 tons. In Problem 2, this paper adopts the research method of life cycle cost (LCC). The model quantifies all the technical, material, human and organizational measures involved in the whole bus system process into cost indicators, and then builds a financial model for the transition of the fleet to a pure electric bus fleet based on the model, which provides a reliable basis for the bus company's decision-making. From a long-term perspective, the public transport company to choose a pure electric bus fleet will be more economically efficient, but need to bear the costly transition to the acquisition of costs. Overall, this paper comprehensively explores the smart bus fleet transformation problem through three complementary models. It provides strong support for decision makers from the perspectives of life cycle cost, financial planning and environmental friendliness. The combined use of these models makes the article more comprehensive and provides useful lessons for future bus fleet transformation.

Keywords: LCA; LCC; Multi-objective Planning; Simulated Anneal.

1. Question Description

In recent years, the rapid spread of electric buses (e-buses) in cities around the world, especially in view of energy consumption and greenhouse gas emissions, has led many cities to re-evaluate the use of conventional diesel buses. In this problem, the group needs to develop the following mathematical model:

In Problem 1, this team needs to develop a mathematical model that integrates various factors, quantitatively considers the ecological consequences of a city's transition to an all-electric bus fleet, and applies the mathematical model in a metropolitan area;

In Problem 2, this team needs to develop a mathematical model that calculates the financial impacts of a city's transition to an all-electric bus fleet. And the model should consider potential external funding and cover up to 50% of the transition costs. Finally, the model will be applied to the previously selected metropolitan area;

2. Model Building

2.1. Models for Problem 1

Life Cycle Assessment (LCA) is a systematic method for comparative analysis of energy saving and emission reduction of urban new energy buses. This paper adopts the LCA method to determine reasonable functional units to account for the energy consumption and greenhouse gas emissions at different stages of the life cycle of each type of bus, so as to quantitatively evaluate and compare the life cycle energy saving and greenhouse gas emission reduction potentials of different buses.

Diesel buses and pure electric buses are selected as research objects. The main technical parameters of each type of bus, such as the total mass and rated passenger capacity, are referenced to the relevant technical parameters of each brand, such as BAIC Foton, Ankai and Yutong, etc. (from China Bus Information Network and China Automotive Network).

Functional unit: Functional unit is a unit of measurement for the functional performance of a product system, which aims to provide standardized input and output data and ensure that the results of life cycle evaluation can be compared. When comparing different products or services, different functional units will produce different life cycle evaluation results, and the appropriate functional unit should reflect the full functionality of the product or system. This study chooses passenger turnover as the functional unit, which not only reflects the basic function of buses to provide travel services, but also can reflect the differences between new energy buses and traditional diesel buses in terms of the rated number of passengers and other aspects. In this paper, the hourly travel service (hourly effective productivity) to meet 1000 person·km is used as the functional unit of evaluation. Among them, travel service (effective productivity) refers to the product of the average effective passenger load and the mileage of travel service in a certain operating time.

System boundary: The research scope of this paper includes the main raw material production stage of buses, vehicle assembly and distribution stage, vehicle driving stage and vehicle scrapping and dismantling stage, as well as the production stage of all types of energy added to the vehicle driving stage, i.e., the production stage of fuel and electric energy.

Life cycle evaluation method: Based on the objectives of this study, when examining the life cycle energy consumption, the indicator is the total calorific value of energy in MJ; when examining the GHG emissions, the IPCC global warming potential is utilized in kg (in CO2 equivalent).

In this study, the energy saving and GHG emission reduction potential of pure electric buses refers to the energy saving and GHG emission reduction potential that can be obtained by replacing diesel buses with pure electric buses, using diesel buses as the reference object.

In particular, the methods of accounting for energy saving potential and greenhouse gas emission reduction potential are shown in equations (1) and (2), respectively.

$$EC = \frac{(ED - EA)}{ED} \times 100\% \tag{1}$$

$$GR = \frac{(GD - GA)}{GD} \times 100\% \tag{2}$$

In the above equation:

1) EC is the energy saving potential (MJ) of a pure electric bus for a given number of trips.
2) ED is the whole life cycle energy consumption of diesel buses in meeting a certain amount of travel services (MJ)
3) EA is the whole life cycle energy consumption of pure electric buses in meeting a certain amount of travel service (MJ)
4) GR is the GHG reduction potential (kg) of pure electric buses for a given number of trips.
5) GD is the whole life cycle GHG emissions of diesel buses for a given number of trips (kg).
6) GA is the GHG emissions of pure electric buses for a given number of trips (kg).

Next **the life cycle data of the bus** needs to be captured:

1) **Bus raw material production stage:** the main consideration is steel, iron, aluminum, copper, magnesium, plastic, glass, rubber, paint and other materials;
2) **Vehicle assembly and distribution phase:** The vehicle assembly phase focuses on the energy consumption and greenhouse gas emissions of the four processes of stamping, welding, painting and final assembly;
3) **Fuel and electric energy production and vehicle driving stage:** this paper will account for energy consumption and GHG emissions from the fuel and electric energy production stage and vehicle driving stage respectively;
4) **Vehicle dismantling and scrapping stage:** after the bus reaches its end-of-life, some of the materials can be recycled after dismantling, crushing, sorting and other processing methods.

Then **life cycle parameters setting** is carried out.

So far, this paper has established a good life cycle evaluation model for buses, and in the model solving, it is necessary to finish collecting relevant data to bring into the model for solving, so that the ecological consequences of a city's transition to an all-electric bus fleet can be found out.

2.2. Models for Problem 2

2.2.1. Diesel Bus (CDB) Life Cycle Cost Analysis and Modeling

The whole life cycle cost of a diesel bus can be composed of acquisition cost, driving and maintenance cost, and decommissioning disposal cost, which include the following.

1) Cost of acquisition (C_A)

The cost of acquisition is a one-time expense or an expense concentrated in a short period of time, including the acquisition cost of traditional automobiles and the cost in the process of acquisition. The former is paid to the automobile manufacturer, that is, demonstration costs, development costs and production costs, is the main part of the cost of acquisition; the latter is used for the consumer in the acquisition process in order to support the development of the acquisition activities, the realization of the purpose of the acquisition of all the costs (such as transportation, inspection, licensing costs, etc.).

The acquisition costing model for diesel buses is:

$$C_A = P + C \tag{3}$$

In Eq. (3): P is the original price of the car; C is the sum of the purchase license fee and related fees.

2) Cost of operation and maintenance ($C_{O\&M}$)

Cost of operation and maintenance ($C_{O\&M}$) refers to the costs required for the use, maintenance and protection of diesel buses after the bus company has taken over the buses. It is the cost paid to ensure the normal operation of diesel buses, including gasoline costs, vehicle maintenance costs, repair costs, spare parts protection costs, insurance premiums, road maintenance costs, etc. The cost of operation and maintenance (CO&M) is the cost incurred by a bus company for the use of diesel buses after it has taken over the buses.

After the purchase of a bus, the bus company enters the utilization stage, i.e. the driving and maintenance stage. The proportion of driving and maintenance costs in LCC is generally 50% ~ 60%, so the cost model of this stage is the key to constitute the LCC model. The cost of this stage mainly consists of operation cost and maintenance:

$$C_M = CO + CM_1 \tag{4}$$

In Eq. (4): C_M is the driving maintenance cost; CO is the fuel consumption cost; CM_1 is the maintenance cost of other parts and components of the bus.

3) Cost of disposal and recycle (C_{DR})

The cost of disposal and recycle (C_{DR}) refers to the cost of various after-treatment of diesel buses after they have been scrapped. This part of the cost accounts for a relatively small portion of the whole life cycle cost of a diesel bus. This is because the residual value of the equipment (C_R) is recovered while paying for the necessary after-treatment (including disposal of scrap, contaminated materials, etc.).

Diesel buses need to be scrapped after a certain number of years of use, and the costs incurred in this process are called end-of-life treatment costs, while there are some parts that can be recycled, so the end-of-life treatment costs and residual value of the equipment as a whole cost of C_{DR}. the calculation model is as follows:

$$C_{DR} = \frac{C_A - C_S}{R} \tag{5}$$

In Eq. (5): C_{DR} is the cost of end-of-life treatment; R is the end-of-life period (10,000 kilometers); C_A is the purchase price of the vehicle; C_S is the residual value of recycling.

2.2.2. Electric bus (BEB) Life Cycle Cost Analysis and Modeling

The whole life cycle cost of an electric bus can be composed of acquisition cost, driving and maintenance cost, and decommissioning disposal cost, including the following.

1) Cost of acquisition (C_A)

As with diesel buses, the acquisition cost is a one-time expenditure or an expenditure concentrated in a short period of time, and consists of both the acquisition cost of electric buses and the cost during the acquisition process.

$$C_A = P + C \tag{6}$$

2) Cost of operation & maintenance ($C_{O\&M}$)

The cost of operation and maintenance of electric buses is roughly the same as that of diesel buses, except that the cost of fuel is replaced by the cost of charging (mainly electricity), so the model can be expressed as follows:

$$C_M = CO + CM_1 \tag{7}$$

In Eq. (7): C_M is the cost of driving maintenance; CO is the cost of battery operation; CM_1 is the cost of maintenance of other EV components.

The operating costs of electric buses are mainly the charging cost (the price of electricity) and the cost of batteries, which can be expressed as follows:

$$CO = DCD \times \frac{N}{T} \tag{8}$$

In Eq. (8): CO is the battery operating cost; DCD is the unit charging tariff (yuan/kWh); N is the charging capacity of the vehicle per 100 kilometers (kWh); and T is the battery charging efficiency.

The reliability is a function of time t, so it is also called the reliability function R(t). In this paper, reliability mainly refers to the reliability of rechargeable batteries for electric buses, which is defined as follows:

$$R(t) = P(T > t) \tag{9}$$

Eq. (9): t is the specified time; T is the battery life.

The reliability function R(t) describes the probability that the rechargeable battery is intact in the time period (0,t), R(0) = 1, R(∞) = 0. If the battery starts to work at t=0, and the battery is not powerful enough at the time t, there are still [N-n(t)]/N parts that can work normally.

The estimated value of R(t) is:

$$R(t) = \frac{[N - n(t)]}{N} \tag{10}$$

Battery reliability is one of the determinants of LCC for EVs, and its qualitative relationship with acquisition cost, O&M cost, and LCC can be depicted in Figure 1, where R* denotes the reliability corresponding to the lowest LCC.

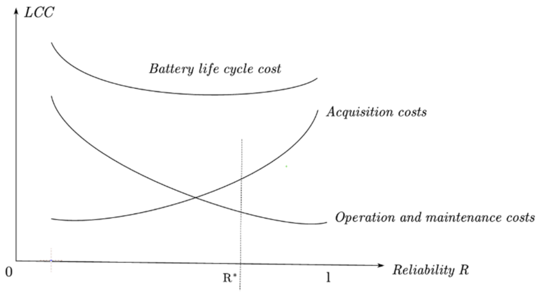


Figure 1. Battery reliability versus LCC

From the above analysis, it can be concluded that the power performance of the battery decreases over time, so the maintenance cost of the battery increases. For the maintenance cost of power battery of electric bus, this paper estimates the battery maintenance cost based on the theory of battery reliability. The formula is as follows:

$$CM_1 = flour(\frac{T_0}{MTTF})(P + C_{MCCRC}) \tag{11}$$

In Eq. (10): T is the service life of the electric vehicle; MTTF is the service life of the battery; flour (T_O/MTTF) is the number of battery components to be replaced in time T; P is the unit price of the battery; C_{MCCRC} is the cost of labor and materials used to maintain the battery when the equipment is replaced.

3) Cost of disposal and recycle (C_{DR})

The cost of disposal and recycle (CDR) refers to the cost of various types of after-treatment for electric buses. The cost structure is the same as that for diesel buses:

$$C_{DR} = \frac{C_A - C_S}{R} \tag{12}$$

3. Model Solution and Result Analysis

3.1. Solution of Model 1 and Analysis of Results

In order to complete the solution of the model of Problem 1, we need to first find the various life cycle data of buses. This paper selects **Beijing** as the research object.

The **first** is the raw material production phase of the vehicle The raw material production phase of the bus is the main material data considered such as steel, iron, aluminum, copper, magnesium, plastic, glass, rubber, paint, and so on. We found the following data from the existing literature [1] (Table 1).

Table 1. Compositions of different buses

Raw materials	Proportions	
	CDB	BEB
steel	53.60%	41.70%
iron	9.20%	7.10%
aluminium	11.80%	9.10%
copper	4.00%	3.20%
magnesium	0.30%	0.30%
plastics	12.20%	9.50%
rubber	0.83%	0.78%
glass	5.10%	4.00%
paint	0.92%	0.79%

Note: CDB is diesel buses, BEB is pure electric buses, the same below.

Second, the energy consumption and greenhouse gas emissions of the four processes of stamping, welding, painting and final assembly in the vehicle assembly and distribution stage. Based on the energy consumption data of vehicle manufacturers for complete vehicle manufacturing, this paper compiles a table of energy consumption for this stage to meet the 1000 person-km hour travel service (Table 2). In the transportation distribution stage of buses, diesel trucks are mostly used for transportation, and the average value of fuel consumption (600 $J\bullet kg^{-1}\bullet km^{-1}$) and transportation distance (1207.44 km) are adopted from the average data of China [2].

Table 2. Energy consumption of 1000 passenger -kilometer service per hour

Assembly phase	CDB			BEB		
	Electricity/MJ	Natural gas/kg	Petrol/kg	Electricity/MJ	Natural gas/kg	Petrol/kg
Stamping	3582.7	0	0	5293.8	0	0
Welding	3078.9	0	0	4549.4	0	0
Livery	11279.8	358.6	0	16667.2	529.8	0
Final assembly	2779.7	0	286.2	4107.4	0	422.9

Third, fuel and electricity production and vehicle driving phase: In this paper, energy consumption and GHG emissions will be accounted for from the fuel and electricity production phase and the vehicle driving phase, respectively. In the electricity production phase, the production data of all kinds of fuels are obtained from the Gabi database for China. The energy efficiency, carbon emission factor and net calorific value coefficient (NCC) are obtained from the Gabi database. In the WTP stage, EF_{WTP} represents the energy efficiency of process fuels consumed in the production of 1 MJ of motor fuels, and GWP_{WTP} represents the global warming potential (in terms of CO_2 equivalent) caused by the production of 1 MJ of motor fuels during the WTP stage. GWP_{PTW} represents the GWP (in terms of CO_2 equivalent)

Table 3. Data of fuel production and driving stages

Bus type	EF_{WTP}/(MJ · MJ^{-1})	GWP_{WTP}/(g·MJ^{-1})	GWP_{PTW}/(g·MJ^{-1})
CDB	0.28	0.28	76.8
BEB	2.14	244.4	0

Finally, there is the vehicle dismantling and scrapping stage, after the bus reaches its end-of-life, some of the materials can be recycled after dismantling, crushing, sorting and other processing methods. According to the research statistics and literature, it can be concluded that the average full-loading rate of buses in Beijing is 0.45, and the operating mileage of hourly travel service is 17.5 km at average speed, and the scrapping mileage is 400,000 km. According to the average full-loading rate as the ratio of effective passenger capacity to rated passenger capacity, the effective passenger capacity of each type of bus can be measured by combining with the rated capacity of each type of bus, while the hourly travel service (effective productivity) is obtained by the product of effective passenger capacity and hourly travel service operating mileage. Therefore, the parameters of each bus type to meet the 1000 person-km hourly travel service can be organized (Table 4).

Table 4. Travel service parameters of 1000 passenger kilometer per hour

Bus type	Rated/effective passenger capacity (Q/q)/person-time	Time Travel Service(W) /(person*km)	Service quantity (N)/vehicle	Service mileage (L)/km	Environmental load factor (F)
CBD	95/42.5	743.75	1.34	23.53	0%
BEB	77/34.5	603.75	1.65	28.98	0.004%

In the above chart:

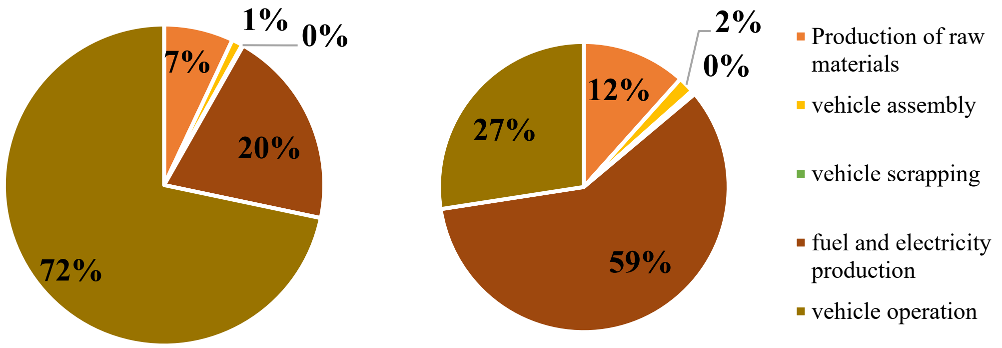
$$N = \frac{X}{l \times p} \tag{13}$$

$$L = \frac{X}{p} \tag{14}$$

$$F = \frac{s}{S} \tag{15}$$

- **N** is the number of buses needed to satisfy a certain travel service in a certain period of time;
- **L** is the service mileage (km) that buses need to operate to satisfy a certain travel service in a certain period of time;
- **F** is the life-cycle environmental loading coefficient;
- **X** is the amount of service to satisfy a certain number of trips in a certain period of time (person·km)
- **l** is the service mileage (km) of bus travel service in a certain period of time;
- **p** is the effective passenger capacity of buses (per son)
- **s** is the average operating mileage (km) of buses in a certain period of time;
- **S** is the mileage of bus to complete the end-of-life in the life of the bus (km).

In terms of model solving, this paper uses **Gabi**, a life cycle evaluation software developed by PE Germany, to carry out the evaluation of life cycle energy consumption and greenhouse gas emissions, and obtains the following results:



CDB BEB

Figure 2. Energy consumption of the two types of buses at different stages of the journey

Table 5. Energy consumption of the two types of buses at different stages of the journey

Energy consumption (MJ)	Production of raw materials	Vehicle assembly	Vehicle scrapping	Fuel and electricity production	Vehicle operation	Total
CDB	30.54	4.73	0.54	87.49	312.48	435.78
BEB	44.22	6.99	1.67	223.26	104.33	380.47

1) Evaluation of energy consumption at different stages of the life cycle: As shown in the above charts, the main life cycle stage energy consumption of diesel buses occurs in the driving stage accounting for 72% of the total life cycle energy consumption, and the main life cycle stage of pure electric buses is the electric energy production stage, accounting for 59% of the total life cycle energy consumption; diesel buses have the second highest energy consumption in the fuel production stage, occupying 20%, and pure electric buses have the second highest energy consumption in the driving stage, occupying 27%; the energy consumption in the vehicle assembly and end-of-life stages is smaller in both types of buses, accounting for less than 3% in both cases.

Table 6. GHG Emissions at Different Stages of the Life Cycle of Various Bus Types

Greenhouse gas emissions (kg)	Production of raw materials	Vehicle assembly	Vehicle scrapping	Fuel and electricity production	Vehicle operation	Total
CDB	2.25	0.27	0.04	4.44	23.99	30.99
BEB	3.06	0.4	0.01	25.5	0.17	29.14

2) Evaluation of GHG emissions at different stages of the life cycle: As can be seen from the above charts, most of the GHG emissions from diesel buses are concentrated in the vehicle driving stage, which accounts for 78% of the total emissions of the whole life cycle, while pure electric buses do not really have "zero GHG emissions", but are shifted to the stage of electric energy production, which accounts for 88% of the total emissions of the whole life cycle.

3) Evaluation of energy saving and greenhouse gas emission reduction: Compared with diesel buses, pure electric buses have an energy saving potential of **12.69%**, and a greenhouse gas emission reduction potential of up to **6.05%** of the greenhouse gas emission reduction potential. If the effective passenger capacity is not taken into account, and only the vehicle service mileage is used as the functional unit of evaluation, the energy saving potential of pure electric buses can reach 20%-30[3], which is larger compared with the results of this paper. The reason is that this study to travel service as a functional unit, and at the same time consider the effective passenger capacity and service mileage two factors, and in general, the effective passenger capacity of new energy buses is relatively low, so the energy saving potential is reduced accordingly, and the effective passenger capacity of the bus on the overall service function of the bus has a certain impact on the energy consumption and greenhouse gas emissions.

4) Scenario Analysis of New Energy Bus Development in Beijing: After inquiring the existing 8,290 buses in Beijing that are not purely electric, accounting for 34.9% of the total, the passenger turnover borne by the regular buses in Beijing is about 32.8.5 billion person-km, according to the results of the study on energy saving and greenhouse gas emission reduction potential of buses, it is estimated that replacing the bus fleet with purely electric ones can save **21.87%** of the energy and bring about **60,700** tons of greenhouse gas emission reduction. The results show that the development of pure electric buses has a **positive effect** on energy saving and greenhouse gas emission reduction in Beijing.

3.2. Solution of Model 2 and Analysis of Results

Analyzing model 2, we can get that the life cycle cost C of new energy buses includes four parts: acquisition cost C_A, driving and maintenance cost C_M, and the title also requires to cover up to 50% of the transition cost C_T and potential external funding C_S. Since the handling fee C and end-of-life treatment cost C_{DR} of the two types of buses are almost the same, these two indicators are not considered.

$$C = C_A + C_M + C_T - C_S \tag{16}$$

$$C_T = c_T \bullet C_A \tag{17}$$

where c_T is the transition cost coefficient, with a size between 0 and 0.5. In this paper, we take 0.1.

Next, we collect various data, and the following is a table of technical parameters and acquisition costs and government subsidized prices for typical CDB and BEB models in Beijing:

Table 7. Comparison of purchase costs and government subsidies of various types of buses

Type	BEB	CDB
Total acquisition cost C_A	170	70
C_{A1}	Power battery:85 Drive motor: 8 Electronic control system: 8	Internal combustion engine:5
C_{A2}	69	65
Government subsidy C_S	50	0
C_A-C_S	120	70

Therefore, the formula for diesel buses (CDB) is:

$$S_1 = C_A + C_M = P + FC \bullet Price_O \bullet \frac{x}{100} \tag{18}$$

Where FC is the 100 km fuel consumption and $Price_O$ is the fuel price. The formula for pure electric bus (BEB) is:

$$S2 = C_A + C_M + C_T - C_S = P + DCD \bullet \frac{N}{T} \bullet \frac{x}{100} + c_T \bullet C_A - C_S \tag{19}$$

Take the gasoline price as the average gasoline price in Beijing in 2023, RMB 8.05/liter, and take the electric bus charging electricity price as the average electricity price in Beijing in 2023, RMB 0.5383/kWh. Then take the 100km fuel consumption of typical diesel buses in Beijing, and the 100km electricity consumption data of typical pure electric buses, and take the charging efficiency T as 0.8 and bring it into the model for calculation.

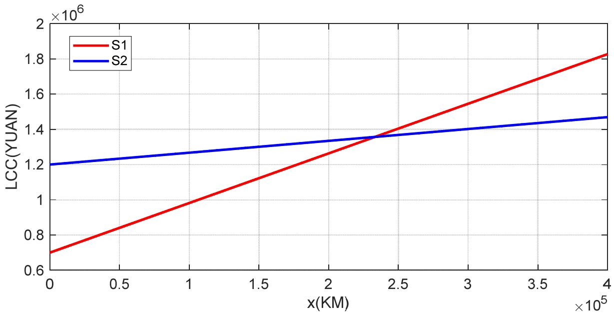


Figure 3. Life cycle cost of CDB vs. BEB vs. kilometers traveled

Above is a plot of life-cycle cost versus kilometers driven for CDBs and BEBs, which shows that CDBs have lower acquisition costs but higher subsequent driving and maintenance costs, whereas the opposite is true for BEBs, and thus BEBs are more economically viable from the perspective of an individual vehicle after approximately 240,000 kilometers of driving.

Next, we model the financial changes in the fleet transition to a pure electric bus fleet, we simplify the model to a fleet of CDBs that are simultaneously replaced with BEBs after xt kilometers of driving, and then compare the financial models with and without the transition. Let the overall financial situation of the bus fleet without transition be Sum1 and the overall financial situation of the bus fleet with transition be Sum2, thus:

$$Sum_1 = CDB \bullet S1(x) + (BUS - CDB) \bullet S2(x) \tag{20}$$

$$Sum_2 = CDB \bullet S1(xt) + (BUS - CDB) \bullet S2(x) \ + \ CDB \bullet S1(x - xt) \tag{21}$$

Taking xt as 100,000km, checking the information to get the number of diesel bus CDB in Beijing is 8290, the number of electric bus BEB is 15451, speaking of these data into the overall financial model can be obtained:

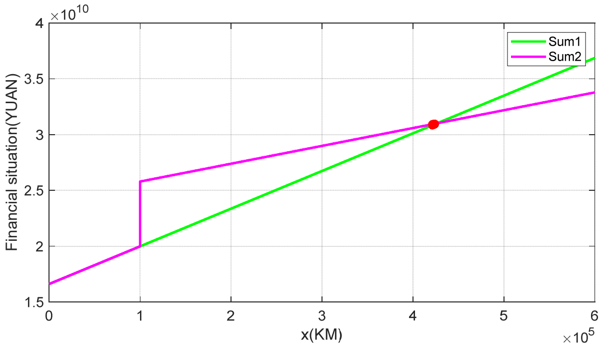


Figure 4. Modeling Financial Changes in Transitioning a Bus Fleet to a Purely Electric Bus Fleet

According to the above figure, we can see that the bus fleet in the transition to pure electric buses will incur a relatively large purchase cost, but in the newly purchased vehicles driving about 320,000km, the transition to pure electric buses compared to the original bus fleet without the transition will appear to be more economically viable, i.e., from the perspective of the long-term perspective, the public transport company to choose a pure electric bus fleet will be more economically viable, but need to bear the cost of the expensive transition to the purchase of the cost.

4. Advantages and Disadvantages

4.1. Advantages

4.1.1. Model 1

1) Model 1 adopts a full life cycle perspective, considering all stages of the life cycle of a bus, including the production, utilization and end-of-life stages. This helps to assess the ecological impact of new energy buses in a more comprehensive manner.

2) The choice of passenger turnover as the functional unit is reasonable as it reflects the primary function of buses, i.e. providing services to passengers. This makes comparisons between different buses more operational.

3) Consideration of multiple energy sources: The model takes into account the multiple energy sources involved in the

production phase, including fuel and electricity. This helps to assess more accurately the energy consumption of different types of buses.

4.1.2. Model 2

1) Model 2 adopts the Life Cycle Cost (LCC) methodology, which comprehensively considers the costs of new energy buses throughout their life cycle, including procurement, driving and maintenance, and end-of-life treatment. The model also provides a detailed cost analysis for each stage of the bus life cycle (procurement, driving and maintenance, end-of-life treatment), including fuel cost, maintenance cost, battery maintenance cost, etc. This helps to assess the costs more accurately. This helps to more accurately assess the contribution of each cost to the total cost.

2) The model introduces transition costs, which take into account the additional costs that may be involved in the transition from conventional to purely electric buses. This is a common scenario in practice and provides a more realistic financial picture for the process of upgrading and migrating a bus fleet.

4.2. Disadvantages

4.2.1. Model 1

1) The reliability of LCA is highly dependent on the accuracy of the data. If the data used in the model is not accurate or comprehensive enough, the assessment results may be affected.

2) LCA methods are usually complex in terms of model construction and solution, requiring large amounts of data and computational resources. This may increase the difficulty of the model and the cost of implementation.

3) Despite the choice of passenger turnover as the functional unit, it may still be limited by some specific circumstances. In different cities or operating environments, it may be more appropriate to choose other functional units.

4.2.2. Model 2

1) The model's estimation of costs is highly dependent on accurate data, including procurement costs, driving and maintenance costs, and so on. If these data are inaccurate or incomplete, it will affect the model's results.

2) The transition cost coefficient (cT) in the model is a parameter that needs to be chosen, which determines the weight of transition costs in the total costs. The choice of this coefficient may have some impact on the results, so it needs to be chosen rationally or determined through sensitivity analysis.

References

[1] WANG Ning, GONG Zaiyan, MA Jun. Prospect analysis of hybrid and pure electric bus development based on economic and emission benefits[J]. China Soft Science,2011(12):57-65.

[2] LIN Xiaodan, TIAN Liang, LU Bin et al. Analysis of energy saving and emission reduction benefits of pure electric buses based on travel service[J]. Environmental Science,2015, 36(09): 3515-3521.DOI:10.13227/j.hjkx.2015.09.050.

[3] Zhou B. Research on electric bus traveling scheduling based on improved genetic algorithm[D]. Changsha University of Technology, 2012.