Battery Electric Bus Selection Based on Entropy Weight Method and Road Operation Test: Using Nanjing Bus Company as an Example

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Before putting battery electric buses into actual daily operations, the selection of buses is of great importance to the bus companies and the improvement of energy efficiency. Based on multi-dimension big data provided by the Nanjing Bus Company and by adopting the entropy weight method and road operation test, this paper presented an objective method for the selection of battery electric bus. Each of these four enterprises, BYD, Kaiwo, Yinlong, and Jiankang which were commonly seen in the Chinese market, provided two types of battery electric buses. Four different routes were selected for the road test and collected over 50 days of daily operation test data. In order to reflect all aspects of the vehicle performance, eight indexes which had been considered and designed comprehensively were classified into three categories: reliability, economy, and security. Together with the road operation data, an evaluation system based on the bus’s daily operation performance was established through the entropy weight method. Assessing results showed that battery electric bus with better performance usually had a total evaluation score over 0.69. Generally, electric buses with high scores on one route also had higher scores on all the other routes, such as brand D. But, on unimpeded routes, results may differ, for example, in route 134 W, 10-meter buses of brand B ranked first. In contrast to earlier studies, the selection result obtained by this method was more objective and intuitive, which was also consistent with the actual scenario. The selection process indicates that this method is highly practical and can be easily carried out. Therefore, we can assume that the proposed method can evaluate the actual operation state of battery electric buses and provides a new selection way.

1. Introduction

1.1. Development of Battery Electric Buses in China. In recent years, China has been focusing on the amelioration of environmental pollution and has listed the pollution caused by traffic emission as an imminent matter which cannot be underestimated. In order to protect the environment, optimize the air quality, and maintain or even improve the well-being of the people, the Chinese government issued the Energy Saving and New Energy Automobile Industry Development Plan as early as 2012. This report emphasized that to promote sustainable development of the automobile industry, it is essential to accelerate the transformation and upgrading of the industry as well as vigorously develop energy-saving vehicles and renewable energy vehicles. Meanwhile, having an explicit understanding of the development status and situation and pushing forward the technological research and industrialization will contribute to China’s transformation from a big country of automobiles to a powerful one [1]. In May 2019, China’s Ministry of Transport along with 12 ministries and commissions issued the Green Travel Action Plan (2019–2022), which regarded increasing the energy-saving or renewable energy vehicles as a breakthrough point, and proposed to strengthen the further promotion of energy-saving and renewable energy vehicles in many domains (e.g., urban public transport, taxi, and short-distance road passenger transport) [2]. On May 8th of the same year, China’s Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Transport, and National Development and Reform Commission jointly issued the Notice on Supporting the Promotion and Application of New Energy Bus (Finance and
Battery electric, 90.10% for the process of bus electrification. Empirical evidence has proved that those national policies have provided support for the process of bus electrification.

On the other hand, traffic congestion has posed several formidable challenges for contemporary metropolitan districts, which simultaneously stimulate the development of public transportation. As reported, by the end of 2019, China had more than 690,000 hybrid electric buses and is still in a rapid development stage [5]. Among them, renewable energy vehicles accounted for 59%. As exhibited in Figure 1, in 2019, China newly added and replaced 69,000 buses, of which 96% are renewable energy buses, and among these renewable energy buses, 90.10% are battery electric buses. The main brands of the battery electric bus in the Chinese market include Yutong, Zhongtong, CRR Electric, BYD, Golden Dragon, Silver Dragon, Jiankang, Kaiwo, and so on, and the major standards of the battery electric buses in China are 8 meters long and 10 meters long.

At present, most regions in China are vigorously promoting environmental-friendly public transport. For instance, Shenzhen reached full coverage of the electric bus at the end of 2017 with the popularized battery electric buses reaching 16,359. Nanjing’s ownership of battery electric buses had ranked second in the world by December 2019, surpassed only by Shenzhen. Owing to releasing the largest number of renewable energy vehicles at a time, having the largest scale of public charging infrastructure, and making the fastest work progress, Nanjing won the “Global Urban Transport Leadership Award” at the 2015 UN climate change conference [6]. Note that in addition to mitigating the environmental pressure caused by exhaust emission, the penetration of BEVs in the public transport system can bring substantial market opportunities for local battery electric bus production enterprises.

Battery electric buses provide exceptional economic and environmental benefits as well as quieter and more comfortable driving conditions with less noise compared to conventional fuel buses. Moreover, under the working conditions of urgent starts and stops on urban roads, electricity drive makes the driving more stable and provides a better riding experience for passengers. However, battery electric buses are still at the nascent stage given their high purchase price, vast investment in the construction of corresponding infrastructure, high vehicle maintenance costs, and high-tech demands. Meanwhile, there are also some specific problems in the actual operation process, such as short mileage, long charging time, and unbalanced charging stack distribution during peak hours. To address the aforementioned gaps, additional efforts should be made to implement the selection of battery electric buses.

It should be noted that despite the popularization of battery electric buses in most cities across China, battery electric buses are confronted with lower operation efficiency relative to diesel and petrol buses. Therefore, under the support of operation data and with the aim of normal service and operation, when bus companies choose and purchase the electric bus, they should give priority to products with excellent performance and low cost and those which are safe and environmental-friendly.

1.2. Review of Battery Electric Bus Selection Method. The number of battery electric buses is growing rapidly in many Chinese cities. How to scientifically and reasonably select a battery electric bus which is suitable for the city and has an excellent performance is becoming a realistic problem. For this reason, related departments in China have promulgated relevant policies. Enterprises and analysts have also conducted research studies to improve the selection method of battery electric bus, which can be classified into the following categories. These categories and their references are shown in Table 1, and Table 2 shows the comparisons of parameters among different types of batteries.

1.3. Benefits of Using the Entropy Weight Method and Running the Road Operation Test

1.3.1. Limitations of Existing Methods. For the aforementioned methods, reasonable analyses of electric bus performance and EV battery performance can be obtained, but several limitations still exist. (1) Many research studies only focus on parts of the battery electric bus, for example, the battery; however, wanting to select a suitable electric bus for a city needs a comprehensive and elaborate selection method. (2) Due to the lack of time or resources, most selection methods were based on laboratory conditions or analog simulation; therefore, their authenticity cannot be guaranteed. (3) The existing selection method for battery electric buses cannot directly judge the advantages and disadvantages of the bus. (4) In urban areas where road conditions are extremely complex, battery electric buses...
| Selection method         | Characteristics                                                                                       | Description                                                                                                                                                                                                 | Reference                                      |
|-------------------------|--------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| National standards      | So far, China has developed many standards which cover BEVs. On May 12, 2020, three mandatory national standards formulated by the Ministry of Industry and Information Technology were issued by the State Administration for Market Regulation and the Standardization Administration of China, and they have been implemented on January 1, 2021. | Deficiency: these three mandatory national standards are the first mandatory national standards in the field of electric vehicles in China. They coordinate entirely with the international standards and regulations and are based on technology innovation products and the summary of the experience of Chinese electric vehicle industry. They can significantly enhance the safety level of renewable energy vehicles and ensure healthy and sustainable development of the whole industry. However, if the selections only depend on these standards, they will mainly stay at a superficial level of power system and supporting facility. That is, the selection method will be dominated by the price of the vehicle itself along with its supporting facilities, which could not provide holistic insights for the selection. | Safety requirements for electric vehicles (GB 18384-2020) [7]                                                                 |
|                         | It mainly stipulates the electrical safety and functional safety requirements of electric vehicles and adds the requirements for battery system thermal event alarm signals. It also proposes requirements for enhanced vehicle waterproof, insulation resistance, and monitoring system to reduce accident risk. Likewise, the test methods of insulation resistance and capacitance coupling should be optimized in order to improve the test accuracy and ensure the safety of the vehicle’s high voltage. It targets the characteristics of the electric bus such as high passenger volume, large battery capacity, and high driving power. Stricter safety requirements are made for the battery compartment collision, charging system, and vehicle waterproof test conditions and requests, in order to further enhance the ability of preventing fire accidents. | Safety requirements for electric vehicles (GB 38032-2020) [8]                                                                 | Safety requirements for power batteries of electric vehicles (GB 38031-2020) [9]                                                                 |
| Selection method                               | Characteristics                                                                 | Description                                                                                                                                                                                                 | Reference          |
|-----------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Battery manufacturing key features            | The core of a battery electric bus is its battery; through the improved random   | The mathematical process and limitations of different Kalman filter (KF) family algorithms suitable for the model-based online state of charge (SOC) estimation were studied. Moreover, KF family algorithms were implemented in model-based online                     | Liu et al. [10]    |
|                                               | forest (RF) technique, Liu et al. designed a data-driven framework which can not only quantify the importance levels of four key battery manufacturing features but also estimate the association among features. Apart from that, based on the Gaussian process regression (GPR) technology with various automatic relevance determination (ARD) kernels, Liu et al. developed an advanced machine learning approach which is able to predict the battery electrode mass load and determine weights of feature variables. The mathematical process and limitations of different Kalman filter (KF) family algorithms suitable for the model-based online state of charge (SOC) estimation were studied. Moreover, KF family algorithms were implemented in model-based online SOC estimation processes which could push the development of battery management systems (BMS), especially electric vehicle (EV) application. A battery management system which could evaluate the SOC of the EV battery was built through the new adaptive extended Kalman filter (AEKF) algorithm. Pulse discharge and customized dynamic stress tests have been conducted indicating that the proposed AEKF has superior performance than compressed extended Kalman filter (CEKF) under dynamic load conditions. Unbalanced battery cell voltage which may reduce storage capacities or even cause explosions or fires is a major obstacle for safe and optimum operations of EVs. Therefore, it is important to grasp cell equalization techniques suitable for EVs. A comprehensive analysis of recent techniques on operation, construction, and control strategy of equalization circuits was also presented. With the increasing demand for lithium-ion batteries in EVs, the new dual forgetting factor-based adaptive extended Kalman filter (DFFAEKF) which has a highly accurate and low-cost state estimation has been proposed for the BMS. Experimental results indicated that under dynamic operating conditions, the combined SOC and SOE (state of energy) estimation method using the proposed DFFAEKF could estimate the battery states with tiny error. | Liu et al. [11]    |
|                                               | EV battery management system                                                    | Battery management system which could evaluate the SOC of the EV battery was built through the new adaptive extended Kalman filter (AEKF) algorithm. Pulse discharge and customized dynamic stress tests have been conducted indicating that the proposed AEKF has superior performance than compressed extended Kalman filter (CEKF) under dynamic load conditions. Unbalanced battery cell voltage which may reduce storage capacities or even cause explosions or fires is a major obstacle for safe and optimum operations of EVs. Therefore, it is important to grasp cell equalization techniques suitable for EVs. A comprehensive analysis of recent techniques on operation, construction, and control strategy of equalization circuits was also presented. With the increasing demand for lithium-ion batteries in EVs, the new dual forgetting factor-based adaptive extended Kalman filter (DFFAEKF) which has a highly accurate and low-cost state estimation has been proposed for the BMS. Experimental results indicated that under dynamic operating conditions, the combined SOC and SOE (state of energy) estimation method using the proposed DFFAEKF could estimate the battery states with tiny error. | Shrivastava et al. [12] |
|                                               | EV battery cell equalization techniques                                         | Battery management system which could evaluate the SOC of the EV battery was built through the new adaptive extended Kalman filter (AEKF) algorithm. Pulse discharge and customized dynamic stress tests have been conducted indicating that the proposed AEKF has superior performance than compressed extended Kalman filter (CEKF) under dynamic load conditions. Unbalanced battery cell voltage which may reduce storage capacities or even cause explosions or fires is a major obstacle for safe and optimum operations of EVs. Therefore, it is important to grasp cell equalization techniques suitable for EVs. A comprehensive analysis of recent techniques on operation, construction, and control strategy of equalization circuits was also presented. With the increasing demand for lithium-ion batteries in EVs, the new dual forgetting factor-based adaptive extended Kalman filter (DFFAEKF) which has a highly accurate and low-cost state estimation has been proposed for the BMS. Experimental results indicated that under dynamic operating conditions, the combined SOC and SOE (state of energy) estimation method using the proposed DFFAEKF could estimate the battery states with tiny error. | Shrivastava et al. [13] |
|                                               | Battery state evaluation                                                        | Battery management system which could evaluate the SOC of the EV battery was built through the new adaptive extended Kalman filter (AEKF) algorithm. Pulse discharge and customized dynamic stress tests have been conducted indicating that the proposed AEKF has superior performance than compressed extended Kalman filter (CEKF) under dynamic load conditions. Unbalanced battery cell voltage which may reduce storage capacities or even cause explosions or fires is a major obstacle for safe and optimum operations of EVs. Therefore, it is important to grasp cell equalization techniques suitable for EVs. A comprehensive analysis of recent techniques on operation, construction, and control strategy of equalization circuits was also presented. With the increasing demand for lithium-ion batteries in EVs, the new dual forgetting factor-based adaptive extended Kalman filter (DFFAEKF) which has a highly accurate and low-cost state estimation has been proposed for the BMS. Experimental results indicated that under dynamic operating conditions, the combined SOC and SOE (state of energy) estimation method using the proposed DFFAEKF could estimate the battery states with tiny error. | Shrivastava et al. [15] |
|                                               | Battery manufacture and performance                                             | Battery management system which could evaluate the SOC of the EV battery was built through the new adaptive extended Kalman filter (AEKF) algorithm. Pulse discharge and customized dynamic stress tests have been conducted indicating that the proposed AEKF has superior performance than compressed extended Kalman filter (CEKF) under dynamic load conditions. Unbalanced battery cell voltage which may reduce storage capacities or even cause explosions or fires is a major obstacle for safe and optimum operations of EVs. Therefore, it is important to grasp cell equalization techniques suitable for EVs. A comprehensive analysis of recent techniques on operation, construction, and control strategy of equalization circuits was also presented. With the increasing demand for lithium-ion batteries in EVs, the new dual forgetting factor-based adaptive extended Kalman filter (DFFAEKF) which has a highly accurate and low-cost state estimation has been proposed for the BMS. Experimental results indicated that under dynamic operating conditions, the combined SOC and SOE (state of energy) estimation method using the proposed DFFAEKF could estimate the battery states with tiny error. |                     |
|                                               | EV battery electric bus                                                         | Machine learning techniques were applied to study experimental aging data gathered from different batteries. They designed the combined LSTM + GPR model and achieved effective future capacities and RUL prediction for lithium-ion batteries. Combined with battery electric bus operations in Beijing, the incremental capacity analysis (ICA) and the differential voltage analysis (DVA) method were used to quantitatively study the aging process of the electric vehicle battery, in a repeatable lab environment. When comparing parameters of lead acid battery, nickel battery, and lithium battery, lithium battery ranks first in the aspects of specific energy, energy density, and number of charge and discharge cycle, followed by nickel battery and lead acid battery. Operating temperature of these batteries focuses on $-25\ldots60^\circ\text{C}$. Lead acid battery is low in maintenance rate, but it is toxic, causes pollution, and has short lifespan. Nickel battery is safe and environmental-friendly, but it also has defects like low overvoltage tolerance or high price. Lithium battery has the advantages of long lifespan and short charging time, but it is expensive and has low overvoltage tolerance. Comparisons of parameters among different types of batteries are shown in Table 2. |
|                                               | In the selection of battery electric bus, predicting future capacities and remaining useful life (RUL) with uncertainty quantification is a significant issue | Machine learning techniques were applied to study experimental aging data gathered from different batteries. They designed the combined LSTM + GPR model and achieved effective future capacities and RUL prediction for lithium-ion batteries. Combined with battery electric bus operations in Beijing, the incremental capacity analysis (ICA) and the differential voltage analysis (DVA) method were used to quantitatively study the aging process of the electric vehicle battery, in a repeatable lab environment. When comparing parameters of lead acid battery, nickel battery, and lithium battery, lithium battery ranks first in the aspects of specific energy, energy density, and number of charge and discharge cycle, followed by nickel battery and lead acid battery. Operating temperature of these batteries focuses on $-25\ldots60^\circ\text{C}$. Lead acid battery is low in maintenance rate, but it is toxic, causes pollution, and has short lifespan. Nickel battery is safe and environmental-friendly, but it also has defects like low overvoltage tolerance or high price. Lithium battery has the advantages of long lifespan and short charging time, but it is expensive and has low overvoltage tolerance. Comparisons of parameters among different types of batteries are shown in Table 2. | Liu et al. [16]     |
|                                               | To create durable electric vehicles, the prediction of battery calendar aging is a critical issue | Machine learning techniques were applied to study experimental aging data gathered from different batteries. They designed the combined LSTM + GPR model and achieved effective future capacities and RUL prediction for lithium-ion batteries. Combined with battery electric bus operations in Beijing, the incremental capacity analysis (ICA) and the differential voltage analysis (DVA) method were used to quantitatively study the aging process of the electric vehicle battery, in a repeatable lab environment. When comparing parameters of lead acid battery, nickel battery, and lithium battery, lithium battery ranks first in the aspects of specific energy, energy density, and number of charge and discharge cycle, followed by nickel battery and lead acid battery. Operating temperature of these batteries focuses on $-25\ldots60^\circ\text{C}$. Lead acid battery is low in maintenance rate, but it is toxic, causes pollution, and has short lifespan. Nickel battery is safe and environmental-friendly, but it also has defects like low overvoltage tolerance or high price. Lithium battery has the advantages of long lifespan and short charging time, but it is expensive and has low overvoltage tolerance. Comparisons of parameters among different types of batteries are shown in Table 2. | Liu et al. [17]     |
|                                               | To study the aging process of the electric vehicle battery                     | Machine learning techniques were applied to study experimental aging data gathered from different batteries. They designed the combined LSTM + GPR model and achieved effective future capacities and RUL prediction for lithium-ion batteries. Combined with battery electric bus operations in Beijing, the incremental capacity analysis (ICA) and the differential voltage analysis (DVA) method were used to quantitatively study the aging process of the electric vehicle battery, in a repeatable lab environment. When comparing parameters of lead acid battery, nickel battery, and lithium battery, lithium battery ranks first in the aspects of specific energy, energy density, and number of charge and discharge cycle, followed by nickel battery and lead acid battery. Operating temperature of these batteries focuses on $-25\ldots60^\circ\text{C}$. Lead acid battery is low in maintenance rate, but it is toxic, causes pollution, and has short lifespan. Nickel battery is safe and environmental-friendly, but it also has defects like low overvoltage tolerance or high price. Lithium battery has the advantages of long lifespan and short charging time, but it is expensive and has low overvoltage tolerance. Comparisons of parameters among different types of batteries are shown in Table 2. | Liu et al. [18]     |
|                                               | Different battery technologies suitable for electric vehicles                  | Machine learning techniques were applied to study experimental aging data gathered from different batteries. They designed the combined LSTM + GPR model and achieved effective future capacities and RUL prediction for lithium-ion batteries. Combined with battery electric bus operations in Beijing, the incremental capacity analysis (ICA) and the differential voltage analysis (DVA) method were used to quantitatively study the aging process of the electric vehicle battery, in a repeatable lab environment. When comparing parameters of lead acid battery, nickel battery, and lithium battery, lithium battery ranks first in the aspects of specific energy, energy density, and number of charge and discharge cycle, followed by nickel battery and lead acid battery. Operating temperature of these batteries focuses on $-25\ldots60^\circ\text{C}$. Lead acid battery is low in maintenance rate, but it is toxic, causes pollution, and has short lifespan. Nickel battery is safe and environmental-friendly, but it also has defects like low overvoltage tolerance or high price. Lithium battery has the advantages of long lifespan and short charging time, but it is expensive and has low overvoltage tolerance. Comparisons of parameters among different types of batteries are shown in Table 2. | Chen et al. [20]    |
| Selection method | Characteristics | Description | Reference |
|------------------|-----------------|-------------|-----------|
| Laboratory and computer simulation models | AVL_Cruise software | Taking a certain BEV as the research object, a whole vehicle simulation model was established based on the design objective. While other components were determined, the influence of different motor characteristics on the vehicle’s dynamic performance was compared and evaluated using the AVL_Cruise software. | Chen et al. [21] |
| Laboratory and computer simulation models | Correlation function models | Qian et al. published a patent proposing a method for assessing the health condition of electric buses’ battery. They established the correlation function models among battery health state, stress condition, remaining capacity, and ohms resistance and conducted a real-time online assessment of battery health status with the operation data. | Qian et al. [22] |
| Laboratory and computer simulation models | Electric bus energy consumption model | Islamaka et al. collected and analyzed the Transjakarta Corridor 1 driving cycle data. They adopted MATLAB/Simulink to build an electric bus energy consumption model and tested the model by comparing the BYD C6 and ITB electric buses. Their model provided a new insight into the evaluation of battery performance. | Islamaka et al. [23] |
| Laboratory and computer simulation models | A more real and accurate health assessment method for the electric bus’s battery was provided | By studying operation data and simulation models presented in the previous studies, Mahmoud et al. compared the characteristics of different types of electric buses (namely, hybrid, fuel cell, and battery). | Mahmoud et al. [25] |
| Comprehensive literature reviews and data collections | Comparing different electric buses’ characteristics | Based on the fuzzy strength, weaknesses, opportunities, and threats (SWOT) approach and fuzzy linear programming, 4 different types of new energy vehicles were compared. | Bubar et al. [26] |
| Comprehensive literature reviews and data collections | Comparing different types of new energy vehicles’ characteristics | The development of battery electric buses and technical specifications critical to the operations of electric bus systems were studied. Three remedy methods were also proposed to widen the operation range, along with a comprehensive analysis on the pros and cons of each method. | Li [27] |
| Comprehensive literature reviews and data collections | Studying electric bus system operation’s technical specifications | A multi-criteria decision-making model was proposed for evaluating the electric bus by utilizing analytic hierarchy process (AHP) and Technique for Order Preference by Similarity to Ideal Solution. EV-2 electric buses outperformed other alternatives in the test. | Hamurcu and Eren [28] |
| Multiple criteria decision-making method (MDCM) | Electric bus evaluation model | Based on best-worst method and MARCOS (Measurement of Alternatives and Ranking according to COmpromise Solution) approaches, an integrated MCDM model for the selection of hydrogen bus was built. Result shows that co-generated electricity from a municipality cogeneration power plant is the best choice. | Pamucar et al. [29] |
| Multiple criteria decision-making method (MDCM) | Hydrogen bus selection method | Utilizing the MCDM method based on charging rate, driving range, battery life, and cost, an EV Li-ion battery selection methodology was proposed. | Logathan et al. [30] |
| Multiple criteria decision-making method (MDCM) | EV Li-ion battery selection methodology | Using the MCDM method which was based on 8 criteria and 4 evaluation methods, an EV infrastructure selection model was built. A way to select HEVs for developing country was made utilizing MCDM technique. Its criteria were selected in terms of economy, social, and environment. | Vytautas et al. [31] |
| Multiple criteria decision-making method (MDCM) | EV infrastructure selection model | | Khan et al. [32] |
| Production enterprises’ road test | HEV selection for developing countries | | |
| Production enterprises’ road test | Vehicles will be tested by the battery electric bus production enterprises before entering the market. These tests cover all kinds of performance indexes, such as mileage and battery capacity. However, most of the tests are carried out on closed roads, while the real road conditions that battery electric buses in cities mostly encounter are more complicated than the closed ones. Also, in a real bus drive, frequent starts and stops are needed for passengers to get on and get down or when it comes to a red light. Therefore, the vehicle data gathered from the road test implemented by the manufacturer cannot accurately reflect a comprehensive performance of a battery electric bus in actual operation. | | |
| Selection method            | Characteristics                                                                 | Description                                                                                                                                                                                                 | Reference     |
|-----------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|
| Road test of the bus company | Evaluation based on AHP and TOPSIS                                              | By using the analytic hierarchy process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), different potential electric bus alternatives were evaluated and compared.              | Hamurcu and Eren [28] |
|                             | Selection based on road tests and case study.                                   | A framework for the selection of battery electric buses based on road tests was formulated, and a case analysis was introduced. This framework contained the design of organization structure, the selection of test vehicles, indexes, and bus routes. |               |
|                             | Deficiency: this method provides a state-of-the-art framework for the selection of battery electric buses. However, due to its lack of road test indexes and relative simple selection and comparison method, it was unable to compare and test the comprehensive performance of vehicles in an in-depth and scientific way. | Based on the road driving test, a multi-objective selection method for battery electric buses was proposed. By using the fuzzy analytic hierarchy process, an index system of the performance evaluation was built. Two typical buses from multiple angles were evaluated, and a better model was selected. |               |
|                             | Deficiency: due to the high reliance on expert experience, the AHP method did not have strong objectivity. Therefore, the results obtained could be potentially unreasonable and inaccurate. |                                                                                                                                  |               |
need to reach the normal operation demands as far as possible. Therefore, more authentic road tests with more comprehensive indexes are needed for the evaluation of battery electric buses.

### 1.3.2. The Benefit and Necessity of Using the Entropy Weight Method and Running the Road Operation Test

Based on the above discussions, this article adopted the entropy weight method and gathered the data from road operation tests, where both the results’ comprehensiveness and practicality can be taken into account simultaneously. Several benefits and necessities of using this method are as follows. First, running the road operation test under real city traffic conditions is the most direct way of selecting the battery electric bus, and the features of selected bus are most suitable for local conditions. Second, the weights of corresponding indexes can be easily and objectively calculated. Third, no other data are needed except those from the road operation test, so different from scoring by experts, this method can guarantee the authenticity and objectivity of the results.

### 1.4. Method Process Flowchart

The structure of the article is as follows. Section 1 presents a brief introduction about battery electric bus selection. Section 2 gives a detailed description of battery electric bus’s technical and operational characteristics. Section 3 mainly describes the road operation test and the data gathering process. Section 4 introduces the entropy weight method and the process of performance evaluation method. In Section 5, an example based on Nanjing Bus Company is given to prove the validity of this model, while the major findings, recommendations, and future research directions are concluded in Section 6.

The process of running the road operation test and using the entropy weight method is shown in Figure 2.

### 2. Analysis of Battery Electric Bus Characteristics

Electric bus refers to a kind of renewable energy bus which uses onboard electricity as its power. To have a comprehensive understanding of the factors for electric bus selection and ensure the reliability of the road test, it is necessary to comprehend the basic technical characteristics and operational characteristics of the electric bus.

#### 2.1. Technical Characteristics of the Battery Electric Bus

The technical characteristics of the battery electric bus are discussed based on the nature of the electric bus itself, mainly the characteristics of the power system. The main technical characteristics are as follows:

1. Electric energy providing power: the battery electric bus has replaced fuel with electric energy, which fundamentally changes the power driving mode of the traditional automobile. New technological changes have emerged, changing the characteristics that traditional buses once had: the need of fossil fuel. Last, from the perspective of power service, battery electric bus is a new type of electricity demand.

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Table 2: Comparisons of parameters among different types of batteries [20].

| Battery type      | Specific energy (Wh/kg) | Energy density (Wh/L) | Operating temperature (°C) | Charge and discharge cycle (times) | Disadvantages                                  | Advantages                                      |
|-------------------|-------------------------|-----------------------|-----------------------------|-----------------------------------|----------------------------------------------|-----------------------------------------------|
| Lead acid battery | 30~50                   | 73.74                 | −20~60                      | 200~350                           | Toxic, pollution, short lifespan              | Low maintenance rate                          |
| Nickel battery    |                         |                       |                             |                                   |                                              |                                               |
| NiCd (nickel-cadmium) | 40~60                 | 120                   | −30~60                      | ≥1000                             | Toxic                                         | Recyclable                                     |
| NiMH (nickel metal hydride) | 60~120                 | 135                   | −20~60                      | 3000                              | Low overvoltage tolerance                     | Safe                                          |
| NiZn (nickel-zinc) | 60                      | 90                    | −30~65                      | ≥1000                             | Expensive                                     | Safe, environmentally friendly, long lifespan |
| NiFe (nickel-iron) | 10~25                   | 58~83                 | −20~50                      | 3600                              | High self-discharge rate                      | Economical, reliable                          |
| Lithium battery   |                         |                       |                             |                                   |                                              |                                               |
| LTO               | 50~90                   | 100~200               | −30~55                      | 8000~20000                       | Expensive, bilge gas problem                  | Low-temperature working environment, long lifespan, short charging time |
| LFP               | 150                     | 240                   | −30~60                      | 1000~2000                        | Low overvoltage tolerance                     | Safe, low self-discharge rate                  |
| LiPo              | 130~250                 | 150~300               | −20~60                      | 5000                              | Different charge and discharge current outputs | Long charging duration, long lifespan          |
| Other types       | Na-NiCl2                | 100~140               | 150~190                     | −40~50                           | ≥2000                                        | High inside temperature, heat loss             | Safe, economical                              |

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(2) Simple structure and convenient maintenance: the battery electric bus has no complex transmission mechanism or exhaust system, but with very simple structure, it can realize four-wheel drive. Moreover, it has a larger internal space and is easier to repair.

(3) Energy conservational and environmentally friendly: the battery electric bus emits no harmful gases, which can achieve zero pollution. Due to the high energy conversion efficiency of the power plant and more advanced pollution reduction and control equipment, when the power plant emissions are calculated according to the power consumption, the pollution generated is far lower than that of traditional buses. Furthermore, in a congested environment such as the city, the energy-saving advantage of electric vehicles is again highlighted.

2.2. Operation Characteristics of the Battery Electric Bus. The operation characteristics of electric buses are discussed according to the economic indexes of battery electric buses. Their main operation characteristics are as follows:

(1) Short mileage: limited by the battery capacity, current mileage of most battery electric buses is about 400 km, which is shorter than that of traditional buses [5].

(2) Long charging duration: in 2019, the average daily charging duration of battery electric buses in China was 1.8 hours. The charging peak is from 10:00 pm to 4:00 am the next day, and another small charging peak is at noon. It takes 3–6 hours for a slow charge bus and 10–30 minutes for a fast charge bus to be fully charged. However, the gap between most bus shifts is 3–10 minutes, and battery electric bus vehicles cannot be fully charged within such interval between adjacent shifts, thus affecting the normal operation. Therefore, battery electric buses are generally charged slowly at night, and a 30–60 minutes’ recharge takes place at noon when the driver takes a rest. Vehicles with large charging power and short charging time adopt the fast charging mode which may cause serious attenuation of the battery capacity, resulting in a sharp decrease of their service life, thus increasing the cost of electric
3. Road Operation Test for Battery Electric Bus

3.1. The Process of Road Operation Tests. The raw data of relevant samples involved in the road operation test of the battery electric bus were collected through the tests. The specific experimental process of the road tests is shown as follows.

3.1.1. Confirming Test Conditions

(1) Selection of Test Vehicles. First, different brands of battery electric buses should be selected with 1–2 representative bus models of the same scale that meet the standard requirements (for example, JT/T1026—2016 battery electric city bus general technical conditions [37]). Note that the usage frequency and damage degree of the selected vehicles should be approximate.

(2) Test Environment. The tests are carried out under the same working condition, the same temperature (such as all in a summer high-temperature environment or all in a cold winter environment), the same humidity (all on sunny days or all on rainy days), and the same route. Note that the routes should be as representative as possible in order to obtain data close to normal daily operation. Four typical city bus routes have been chosen for this road operation test according to their congestion status (from unimpeded to congested) and characteristics. Specific conditions of each bus route are shown in Table 3.

(3) Selection of Test Participants. The person participating in the test should be cautious drivers with experience and without any dangerous driving record. They should receive unified training and have strict workflow awareness to reduce the test data error related to the driver’s behaviors.

3.1.2. Data Collection. Data collected mainly contain objective data. Objective data are mainly vehicle data collected through vehicle-mounted sensors or charging records. Subjective data such as driver's driving experience, passengers’ comfort level, and satisfaction with after-sales service also play a prominent role. However, due to the development of electric buses in recent years, their service is basically on the same level, so only the differences between objective data are considered in this case.

3.1.3. Data Collation and Summarization. The data form is filled out by the driver of the test vehicle and the team managers, as shown in Table 4.

3.2. Road Operation Test Based on Nanjing Bus Company. From August 12 to September 30 in 2017, the Nanjing Bus Company conducted more than one and a half month road test. Each of these four enterprises, BYD, Kaiwo, Yinlong, and Jiankang, provided 2 types of battery electric buses, with vehicle length of 10 meters and 8 meters, respectively. Nanjing Bus Company selected 4 different routes such as Route 134 and Route 302 for the road test to collect daily operation test data. Specific data collection tables are shown in Table 5.

Daily data for one and a half month were gathered from these 32 electric buses and analyzed to obtain the indexes of all battery electric buses in the road test, as shown in Table 6.

Daily road operation data collected between August 12 and September 30 in 2017 are shown in the Supplementary File.

4. Performance Evaluation Method of the Battery Electric Bus Based on the Entropy Weight Method

4.1. Overview of the Entropy Weight Method

4.1.1. Entropy Weight Method. The entropy weight method is an objective value assignment method, which can be used to calculate relevant entropy weight through the index’s variation level and help scholars evaluate the quality of a project more accurately. In general, information theory can determine the order of the system, whereas entropy represents the disorder level. The information entropy of the evaluation index is negatively associated with the variation. Index variation and index weight also has a negative correlation, and their changes are negatively associated. If the value of the evaluation object equals, it means that it is invalid information and needs to be discarded. Reasonable weight can be calculated by the entropy weight method [38].

The weight of each sample’s evaluation index can be determined according to the entropy weight method which has the following advantages:

vehicle battery and making the battery electric bus no longer economical [5, 35, 36].

(3) High requirements for after-sales service: the battery electric vehicle has simple structures, but due to its great difference from the traditional vehicle in power system, traditional workshops lack relevant knowledge and fixing skills. Consequently, professional service engineers are required to perform the maintenance, thus requiring a higher level of after-sales service than traditional buses.
(1) Strong objectivity: compared with AHP, the entropy weight method has strong objectivity and does not rely on the expertise, thus making the result more accurate and reasonable.

(2) Strong adaptability: with robust mathematical theory and adaptability, the entropy weight method can be applied to all operations that need to determine the weight.

However, the entropy weight method also has the following disadvantages:

(1) Strong dependence: the weight of each index in the entropy weight method depends on the sample. If the data are constantly changing, uniformity cannot be formed.

(2) Insufficient objectivity: although part of the subjectivity is effectively eliminated, the weight
calculated by this method is the degree of how useful the information of each index is, which makes this method still lack a certain degree of objectivity.

The road operation test gains a large amount of data, and the value between each index’s data has certain differences, whereas the entropy weight method is an objective weighting method that determines the weight based on the variation range of the index data of each evaluation object. Therefore, based on the differences of the road operation test data, the weight of each index can be obtained objectively. The data of road operation test are suitable to be analyzed and evaluated by the entropy weight method.

### 4.1.2. Using the Entropy Weight Method to Determine the Initial Weight

Standardization is applied to scale the data within a certain range to minimize bias and to ensure that they receive equal dimension [38]. In order to ensure the reliability of the results, 0-1 standardization should be carried out on the initial data of the road operation test results to eliminate the dimension which can be easier for horizontal comparison through

\[
x_{ij} = \begin{cases} 
\frac{x_{ij} - x_{\text{min},j}}{x_{\text{max},j} - x_{\text{min},j}} & \text{if } x_{ij} > 0, \\
\frac{x_{\text{max},j} - x_{ij}}{x_{\text{max},j} - x_{\text{min},j}} & \text{if } x_{ij} < 0,
\end{cases}
\]

where \(x_{ij}\) is the initial sample value of test index of battery electric bus test; \(x_{\text{min},j}\) represents the minimum value of \(j\)-th index of the battery electric bus test; \(x_{\text{max},j}\) is the maximum value of \(j\)-th index of the battery electric bus test; and \(x_{ij}\) defines the standardized values of the index of the test samples.

The entropy weight method is used to calculate the initial weights of the evaluation indexes of the battery electric bus. The basic steps of the entropy weight method are as follows:

1. If there are \(m\) samples and \(n\) indexes to be evaluated, then relevant judgment matrix can be established as

\[
A = (a_{ij})_{m \times n}, \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n).
\]

2. A standardization process will be conducted to transform the indexes into numbers ranging from 0 to 1, so that among the sample data, the differences of the units can be ignored, and the results can be compared horizontally. The matrix \(D\) can be obtained by

\[
D = (d_{ij})_{m \times n}, \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n),
\]

where \(d_{ij}\) is the normalized value of \(a_{ij}\). Then, the proportion of all the values of the \(i\)-th index belonging to the \(j\)-th index can be calculated with

\[
h_{ij} = \frac{1 + d_{ij}}{\sum_{i=1}^{m}(1 + d_{ij})}.
\]

(3) The concept of entropy can define the entropy \(E_j\) of each evaluation index:

\[
E_j = \frac{\sum_{i=1}^{m} h_{ij} \ln h_{ij}}{\ln m}
\]

Then, the following formula can be obtained:

\[
w_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j},
\]

where \(E_j\) is the entropy of the evaluation index, \(n\) is the number of the indexes, and \(w_j\) represents the entropy weight of the \(j\)-th index.

Besides, it should be noted that there are two basic principles when obtaining the entropy weight:

1. The entropy weight of each index is between 0 and 1, with the sum of all weights being 1.
2. The entropy weight reflects the degree of 0 and 1 intensity between indexes and the amount of information contained in each index.

### 4.1.3. The Application of Entropy Weight Method

The entropy weight method has been applied in multiple fields such as system science, economic management, and decision science. Its main purpose is to provide a comprehensive evaluation of multiple indexes [39].

Empirical evidence has suggested that the entropy weight method has a superior ability in dealing with comprehensive assessment issues. Lu and Liu established the comprehensive evaluation model of airports by using the entropy weight method and then evaluated and analyzed whether the current operation mechanism of Chinese airports was suitable and reasonable. The quantitative comprehensive evaluation of China’s five major airports was also carried out [40].

The entropy weight method can be used to compare the changes’ development level of the same thing in different periods. Yang et al. https://dict.youdao.com/w/etal/javascript:void(0) used the entropy weight method to build a comprehensive evaluation system in terms of the development of the green city, using Henan, China, as the study case. Based on the evaluation results, 18 municipalities’ green development levels and ranks over 5 years (2014–2018) were gained, which objectively and accurately reflected the green development level of these cities [41].

In machining, the entropy weight method can also solve the weight allocation problem. Kumar et al. classified the application of the entropy weight method in machining and gave a specific method of using the entropy weight method to solve the multi-objective optimization (MOO) problem. The application of this method could obtain the required weight and improve the whole machining efficiency [42].
Chen et al. used the entropy weight method to calculate the habitat index and water quality index to evaluate river ecosystem health. The evaluation obtained the water ecosystem health status in each year and the main influence factors [43].

The entropy weight method can be combined with other methods to make predictions. The entropy weight method can be combined with other methods to make predictions. D. J. Li and L. Li combined the weight of entropy weight method with three other methods to quantitatively predict the trend of PM2.5’s concentration. Then, they tested the method by predicting the air quality in Guangzhou, China [44].

4.2. Comprehensive Evaluation of Battery Electric Buses. Based on the entropy weight method, \( g_{jz} \) represents the evaluation value of the \( j \)-th battery electric bus’s index \( z \), and \( G_j \) is the total evaluation value. Then, the specific formulas of the comprehensive evaluation model of battery electric bus are as follows:

\[
g_{jz} = \sum_{i=1}^{m} w_i \ast x_{ij}, \tag{7}
\]

\[
G_j = \sum_{z=1}^{n} w_z \ast g_{jz}, \tag{8}
\]

where \( x_{ij} \) defines the \( j \)-th battery electric bus’s standardized value of the index \( i \) and \( w_z \) is the index \( z \)'s weight among the criterion layer, while \( w_i \) represents the index \( i \)'s weight among the index layer.

5. An Example: The Selection of Nanjing Battery Electric Buses

5.1. Construction of Nanjing Battery Electric Bus Selection Index System

5.1.1. Selection and Evaluation Principles of Battery Electric Bus. The selection and evaluation of the battery electric bus should be based on its technology, performance, and characteristics. Then, an evaluation system that conforms to the characteristics and actual development of the battery electric bus can be established. Specifically, the following four principles should be followed:

(1) Highlighting the characteristics of the battery electric bus: the main difference between battery electric vehicles and other renewable energy vehicles is that all the energy used by the battery electric vehicles comes from the power batteries. For the traditional bus evaluation, there are dozens of indexes, including power performance, economic efficiency, and security. In contrast, the evaluation indexes for selecting the battery electric bus should not only include the characteristics of the bus itself but also highlight the specialty of the battery and operation, such as short driving distance and long charging time.

(2) Based on the road operation test data: test data obtained from the road operation test are more abundant and closer to the actual operation situation of battery electric bus. Therefore, it is conducive to the comparative analysis of data and ensures the credibility and rationality of the evaluation index.

(3) Being comprehensive: the evaluation indexes should be selected in terms of safety, economy, reliability, comfort, and convenience to reflect the characteristics and performance of the battery electric buses’ operation.

(4) Being universal: with different operating environments and management patterns, different types of battery electric buses have their own characteristics. So, in different circumstances facing different evaluation objects, the evaluation index should be able to make reliable and reasonable judgments.

5.1.2. Index System Construction. According to the aforesaid evaluation index selection principles, combined with the characteristics of the battery electric bus itself, and through systematic analysis and judgment, the selection evaluation system of Nanjing battery electric bus can be determined as a three-layer structure: target layer, criterion layer, and index layer. The top layer is the target layer, which evaluates the comprehensive level of battery electric buses’ road operation performance. The middle layer is the criterion layer. It compares the comprehensive level of the battery electric bus from several aspects. The evaluation criteria are divided into three categories: reliability, economy, and security. The last layer is the index layer, including factors that evaluate the holistic operation ability of the battery electric bus more comprehensively and specifically. Appropriate evaluation indexes are selected to construct the evaluation index system for the selection of battery electric bus. Note that since the existing production of battery electric vehicles has met relevant national and industrial technical standards, this paper will not consider other factors concerning vehicle equipment manufacturing.

(1) Reliability. Different from other multi-energy hybrid vehicles, battery pack is the only energy source of the battery electric bus, and its reliability is a key factor affecting the performance of the vehicle. For example, battery capacity, charging and discharging efficiency, and driving distance will affect the daily operation and management of battery electric buses.

(2) Economy. The manufacturing cost of battery electric buses does not differ from fuel vehicles of the same length. However, the power battery, as one of the electric bus’s core components, its daily power consumption cost, and maintenance cost account for nearly half of the total cost. The difference in performance also leads to different power consumption per mileage, and the difference in quality results in various degrees of breakdowns.
(3) Security. As an energy-saving and zero-emission vehicle, the battery electric vehicle has become an ideal vehicle for people to travel in the future, but the premise of vehicle operation is to ensure its safety. Besides, excessive charge and discharge, unexpected short-circuit of the battery pack, and extreme temperature battery working environment may cause different degrees of temperature rise to the battery. When the heat reaches a certain degree, high temperature will damage the stability state of the chemicals inside the battery, which will cause burning or even explosion. Therefore, during the drive, temperature variation of the battery, which can cause different degrees of temperature rise to the battery, will damage the stability state of the chemicals inside the battery electric bus.

Specific indexes for the selection evaluation are shown in Table 7.

5.2. Index Calculation Based on Road Operation Test Data

In the current study, based mainly on the road operation test data of the battery electric bus, the evaluation indexes are chosen and quantitatively calculated.

5.2.1. Calculation of Reliability-Related Indexes

(1) Charging Duration. The charging duration of a battery electric vehicle is an important index. If the charging duration is too long, the bus operation schedule may be delayed. Using “charging duration per 100 km” can vividly reflect the charging time, which can be calculated as follows:

\[ t^* = \frac{t}{S} \times 100, \]

where \( t^* \) represents charging duration per 100 km (min/100 km), \( t \) is the charging duration measured in the test day (min), and \( S \) is the test measured mileage (km).

(2) Driving Distance. Continued driving distance refers to the mileage continuously driven by the battery electric bus under the condition of fully charged power battery group and ideal road conditions including air temperature, wind speed, and other conditions. It can be divided into constant speed driving and continuous driving under cycle conditions. The driving distance fluctuation is triggered by the influence of battery pack’s state, weather, environmental factors, and other working conditions. In this thesis, the mileage used as the driving distance is statistically measured by the constant speed method.

(3) Battery Capacity. Battery capacity is one of the most important indexes to measure the performance of a battery. It represents the amount of power released by the battery under certain conditions (discharge rate, temperature, termination voltage, etc.), namely, the capacity of the battery [5].

Rated capacity refers to the minimum amount of power that is stipulated or guaranteed to be discharged from the battery pack under specified discharge conditions during the design and production period. Actual capacity refers to the electric quantity that can be released before the termination voltage under actual discharging conditions. Considering the characteristics of the battery, this thesis uses the rated capacity of the battery as the standard for the battery capacity index.

5.2.2. Calculation of Economy-Related Indexes

(1) Purchase Cost. The market prices of battery electric bus, plug-in hybrid bus, and fuel bus are approximately 0.6 million yuan, 1 million yuan, and 0.5 million yuan, respectively. However, battery electric buses can enjoy the subsidization offered by both central and local governments, so the difference between the purchase cost of battery electric bus and that of fuel bus will be tiny. The purchase cost calculation formula is as follows:

\[ P = P_1 + P_2 + P_3 - P_4, \]  

where \( P \) is the purchase cost (thousand yuan), \( P_1 \) is the bus price (thousand yuan), \( P_2 \) refers to the taxes (thousand yuan), \( P_3 \) represents other expenses (thousand yuan), and \( P_4 \) is the average subsidization per bus (thousand yuan).

(2) Power Consumption per 100 km. “Power consumption per 100 km” is one of the economic indexes crucial to the battery electric bus, similar to the “fuel consumption per 100 km” among traditional fuel vehicles. This index shows the amount of electric power consumed by the vehicle for every 100 km drive. In the test, the calculation formula for power consumption per 100 km is defined as follows:

\[ Q^* = \frac{Q}{S} \times 100, \]

where \( Q^* \) is the power consumption per 100 km (kWh/100 km), \( Q \) represents the power consumption during testing (kWh), and \( S \) indicates the test mileage (km).

5.2.3. Calculation of Safety-Related Indexes

(1) Average Temperature Difference of the Brakes. Brake performance is the most important aspect to reflect the active safety performance of a vehicle. During the braking process, the kinetic energy of the entire vehicle is converted into other forms of energy by the friction between the friction material and the brake, most turning into heat energy, so the temperature of the brake will go up.

Generally speaking, as the brake temperature increases, both the friction coefficient of the brake’s material and the braking performance will decrease. Here, the average temperature difference before and after the braking is defined as a safety evaluation index for the braking system. The smaller the average temperature difference is, the higher the level of braking security can be considered.

\[ T_{\text{average}} = \frac{\sum T_{\text{difference}}}{n} = \frac{\sum (T_{\text{before}} - T_{\text{after}})}{n} \]  

where \( T_{\text{average}} \) is the average temperature difference before and after braking (°C), \( n \) is the number of tests, \( T_{\text{difference}} \) is the average temperature difference before and after braking, and \( T_{\text{before}} \) and \( T_{\text{after}} \) are the temperatures before and after braking.
the temperature difference before and after braking (°C), and \( T_{before} \) and \( T_{after} \) represent, respectively, the temperature before and after the brake is used (°C).

(2) *Bus Failure Rate*. The severity of the failure together with the frequency of failure occurrence can comprehensively judge the failure of battery electric bus. The failure rate in road testing can be considered as the ratio of the number of vehicles breaking down to the total number of vehicles or broken times per unit mileage, as defined by

\[
\text{failure rate} = \frac{\text{number of broken buses}}{\text{total bus number}} \quad \text{or} \quad \frac{\text{broken times}}{\text{total mileage}}
\]

(13)

(3) *Severity of Vehicle Failure*. The severity of the failure can be roughly quantified according to the maintenance time. The longer the maintenance time of a vehicle is, the more serious the failure should be considered. In the test, the calculation formula for failure time is as follows:

\[
T^* = \frac{T}{S} \times 100,
\]

where \( T^* \) is the failure time per 100 km (s/100 km), \( T \) represents the fault time under measured test mileage (s), and \( S \) denotes the test mileage (km).

### 5.3. Comprehensive Score Calculation

According to the road operation test method of Nanjing Bus Company described in Section 3.2 and the collected test data, based on the specific indexes for the selection evaluation of battery electric bus shown in Table 7, the initial data and standardized data of the reliability index in the first criterion layer are shown in Table 8.

According to the basic steps of the entropy weight method shown in Section 4.1, the weights of the above data are calculated. Depending on the entropy weight method, the weights of three reliability indexes, namely, charging duration per 100 km, driving range, and battery capacity, in the first layer are also obtained. The weights of the 10-meter bus are 0.22, 0.37, and 0.41, respectively, and the weights of the 8-meter bus are 0.25, 0.36, and 0.39, respectively.

Similarly, in the second criterion layer, the steps for the standardization of raw data and the initial weight calculation using the entropy weight method are the same as the steps of the first criterion layer. Initial data and standardized data of the economic index in the second criterion layer are shown in Table 9.

### 5.4. Evaluation Results

The total evaluation scores calculated in Section 5.3 were linked with the vehicle number and the brands of the buses. The buses were classified according to the vehicle length (10-meter bus and 8-meter bus) and the driving routes, as shown in Tables 12 and 13.

### 5.5. Result Discussion

It can be seen from Table 12 that for Route 134, the 10-meter battery electric buses of brand B have the highest total evaluation score. For Routes 302 and 646, the scores of D brand buses have reached the top. Therefore, bus companies can give priority to these two brands when purchasing. As revealed in Table 13, for Routes 134, 302, and 638, the 8-meter battery electric buses of brand D have the highest overall evaluation score, indicating that bus companies can give priority to this brand. Note that the overall evaluation scores of the two different length models of brand C are both low, so this brand is not recommended.

Among the test routes, road condition of Route 134 is relatively satisfactory, while Route 302 has been called "the most difficult bus route in Nanjing" by the bus drivers due to...
### Table 8: Initial data and standardized data of the reliability index in the first criterion layer.

| Vehicle length (m) | Vehicle number | Charging duration per 100 km (min) | Driving distance (km) | Battery capacity (kwh) | Charging duration per 100 km | Driving distance | Battery capacity |
|--------------------|----------------|----------------------------------|----------------------|----------------------|-----------------------------|----------------|-----------------|
| 10                 | 4015           | 27                               | 170                  | 255.4                | 0.3182                      | 0.8571         | 0.9853          |
|                    | 4016           | 22                               | 170                  | 255.4                | 0.5455                      | 0.8571         | 0.9853          |
|                    | 4017           | 28                               | 170                  | 255.4                | 0.2727                      | 0.8571         | 0.9853          |
|                    | 4018           | 34                               | 170                  | 255.4                | 0.0000                      | 0.8571         | 0.9853          |
|                    | 3809           | 12                               | 190                  | 258                  | 1.0000                      | 1.0000         | 1.0000          |
|                    | 3808           | 17                               | 190                  | 258                  | 0.7727                      | 1.0000         | 1.0000          |
|                    | 3811           | 17                               | 160                  | 221                  | 0.7727                      | 0.7857         | 0.7907          |
|                    | 3810           | 19                               | 160                  | 221                  | 0.6818                      | 0.7857         | 0.7907          |
|                    | 3725           | 26                               | 50                   | 81.2                 | 0.3636                      | 0.0000         | 0.0000          |
|                    | 3726           | 28                               | 50                   | 81.2                 | 0.2727                      | 0.0000         | 0.0000          |
|                    | 3727           | 26                               | 50                   | 81.2                 | 0.3636                      | 0.0000         | 0.0000          |
|                    | 3728           | 29                               | 50                   | 81.2                 | 0.2727                      | 0.0000         | 0.0000          |
|                    | 3813           | 18                               | 150                  | 230.4                | 0.7273                      | 0.7143         | 0.8439          |
|                    | 3815           | 16                               | 150                  | 230.4                | 0.8182                      | 0.7143         | 0.8439          |
|                    | 3812           | 30                               | 150                  | 230.4                | 0.1818                      | 0.7143         | 0.8439          |
|                    | 3814           | 26                               | 150                  | 230.4                | 0.3636                      | 0.7143         | 0.8439          |
| 8                  | 4011           | 28                               | 140                  | 172.8                | 0.2632                      | 1.0000         | 1.0000          |
|                    | 4012           | 23                               | 140                  | 172.8                | 0.5263                      | 1.0000         | 1.0000          |
|                    | 4013           | 33                               | 140                  | 172.8                | 0.0000                      | 1.0000         | 1.0000          |
|                    | 4014           | 30                               | 140                  | 172.8                | 0.1579                      | 1.0000         | 1.0000          |
|                    | 3801           | 14                               | 80                   | 93.3                 | 1.0000                      | 0.4545         | 0.3710          |
|                    | 3803           | 16                               | 80                   | 93.3                 | 0.8947                      | 0.4545         | 0.3710          |
|                    | 3800           | 18                               | 80                   | 93.3                 | 0.7895                      | 0.4545         | 0.3710          |
|                    | 3802           | 18                               | 80                   | 93.3                 | 0.7895                      | 0.4545         | 0.3710          |
|                    | 3721           | 25                               | 30                   | 46.4                 | 0.4211                      | 0.0000         | 0.0000          |
|                    | 3722           | 27                               | 30                   | 46.4                 | 0.3158                      | 0.0000         | 0.0000          |
|                    | 3723           | 32                               | 30                   | 46.4                 | 0.0526                      | 0.0000         | 0.0000          |
|                    | 3724           | 28                               | 30                   | 46.4                 | 0.2632                      | 0.0000         | 0.0000          |
|                    | 3806           | 19                               | 80                   | 93.3                 | 0.7368                      | 0.4545         | 0.3710          |
|                    | 3807           | 20                               | 80                   | 93.3                 | 0.6842                      | 0.4545         | 0.3710          |
|                    | 3804           | 22                               | 80                   | 93.3                 | 0.5789                      | 0.4545         | 0.3710          |
|                    | 3805           | 21                               | 80                   | 93.3                 | 0.6316                      | 0.4545         | 0.3710          |

### Table 9: Initial data and standardized data of the economic index in the second criterion layer.

| Vehicle length (m) | Vehicle number | Purchase cost (thousand) | Initial data | Standardized data |
|--------------------|----------------|--------------------------|--------------|-------------------|
|                    |                |                          | Power consumption per 100 km (kwh) | Cost | Power consumption per 100 km |
| 10                 | 4015           | 1370                     | 99           | 0.2917            | 0.6486          |
|                    | 4016           | 1370                     | 113          | 0.2917            | 0.2703          |
|                    | 4017           | 1370                     | 89           | 0.2917            | 0.9189          |
|                    | 4018           | 1370                     | 102          | 0.2917            | 0.5676          |
|                    | 3809           | 1440                     | 89           | 0.0000            | 0.9189          |
|                    | 3808           | 1440                     | 93           | 0.0000            | 0.8108          |
|                    | 3811           | 1440                     | 106          | 0.0000            | 0.4595          |
|                    | 3810           | 1440                     | 86           | 0.0000            | 0.3710          |
|                    | 3725           | 1200                     | 119          | 1.0000            | 0.1081          |
|                    | 3726           | 1200                     | 123          | 1.0000            | 0.0000          |
|                    | 3727           | 1200                     | 92           | 1.0000            | 0.8378          |
|                    | 3728           | 1200                     | 102          | 1.0000            | 0.5676          |
|                    | 3813           | 1300                     | 97           | 0.5833            | 0.7027          |
|                    | 4315           | 1300                     | 115          | 0.5833            | 0.2162          |
|                    | 3812           | 1300                     | 98           | 0.5833            | 0.6757          |
|                    | 3814           | 1300                     | 100          | 0.5833            | 0.6216          |
### Table 9: Continued.

| Vehicle length (m) | Vehicle number | Purchase cost (thousand) | Initial data | Standardized data |
|--------------------|----------------|--------------------------|--------------|-------------------|
|                    |                |                          | Power consumption per 100 km (kwh) | Cost | Power consumption per 100 km |
|                    |                |                          | (kwh/100km) |                  |                  |
| 4011               | 970            | 79                       | 0.5263       | 0.6667            |
| 4012               | 970            | 86                       | 0.5263       | 0.4722            |
| 4013               | 970            | 86                       | 0.5263       | 0.4722            |
| 4014               | 970            | 84                       | 0.5263       | 0.5278            |
| 3801               | 1050           | 67                       | 0.1053       | 1.0000            |
| 3803               | 1050           | 80                       | 0.1053       | 0.6389            |
| 3800               | 1050           | 79                       | 0.1053       | 0.6667            |
| 3802               | 1050           | 71                       | 0.1053       | 0.8889            |
| 3721               | 1070           | 85                       | 0.0000       | 0.5000            |
| 3722               | 1070           | 102                      | 0.0000       | 0.0278            |
| 3723               | 1070           | 103                      | 0.0000       | 0.0000            |
| 3724               | 1070           | 85                       | 0.0000       | 0.5000            |
| 3806               | 880            | 75                       | 1.0000       | 0.7778            |
| 3807               | 880            | 81                       | 1.0000       | 0.6111            |
| 3804               | 880            | 83                       | 1.0000       | 0.5556            |
| 3805               | 880            | 83                       | 1.0000       | 0.5556            |

### Table 10: Initial data and standardized data of the security index in the third criterion layer.

| Vehicle length (m) | Vehicle number | Average temperature difference of the brake (°C) | Failure rate (time/100 km) | Failure time per 100 km (s/100 km) | Average temperature difference of the brake | Failure rate | Failure time per 100 km |
|--------------------|----------------|-----------------------------------------------|-----------------------------|-------------------------------------|-------------------------------------------|-------------|-------------------------|
| 4015               | 9              | 0.0000                                        | 0                           | 0.7000                             | 1.0000                                    | 1.0000      | 1.0000                  |
| 4016               | 9              | 0.0000                                        | 0                           | 0.7000                             | 1.0000                                    | 1.0000      | 1.0000                  |
| 4017               | 16             | 0.0094                                        | 6                           | 0.0000                             | 0.9191                                    | 0.9943      |
| 4018               | 14             | 0.0276                                        | 75                          | 0.0000                             | 0.7619                                    | 0.9290      |
| 3809               | 9              | 0.0000                                        | 0                           | 0.7000                             | 1.0000                                    | 1.0000      | 1.0000                  |
| 3808               | 12             | 0.0000                                        | 0                           | 0.4000                             | 1.0000                                    | 1.0000      | 1.0000                  |
| 3811               | 8              | 0.0110                                        | 4                           | 0.8000                             | 0.9051                                    | 0.9962      |
| 3810               | 14             | 0.0000                                        | 0                           | 0.2000                             | 1.0000                                    | 1.0000      | 1.0000                  |
| 3725               | 6              | 0.1160                                        | 811                         | 1.0000                             | 0.0000                                    | 0.2327      |
| 3726               | 7              | 0.0600                                        | 84                          | 0.9000                             | 0.4827                                    | 0.9205      |
| 3727               | 11             | 0.0111                                        | 100                         | 0.5000                             | 0.9044                                    | 0.9054      |
| 3728               | 12             | 0.0331                                        | 1057                        | 0.4000                             | 0.7143                                    | 0.0000      |
| 3813               | 7              | 0.0454                                        | 23                          | 0.9000                             | 0.6088                                    | 0.9782      |
| 3815               | 7              | 0.0395                                        | 166                         | 0.9000                             | 0.6596                                    | 0.8430      |
| 3812               | 8              | 0.0000                                        | 0                           | 0.8000                             | 1.0000                                    | 1.0000      |
| 3814               | 7              | 0.0000                                        | 0                           | 0.9000                             | 1.0000                                    | 1.0000      |
| 4011               | 8              | 0.0180                                        | 5                           | 0.6667                             | 0.8510                                    | 0.9980      |
| 4012               | 8              | 0.0360                                        | 326                         | 0.6667                             | 0.7013                                    | 0.8714      |
| 4013               | 16             | 0.0107                                        | 77                          | 0.0000                             | 0.9113                                    | 0.9096      |
| 4014               | 11             | 0.0000                                        | 0                           | 0.4167                             | 1.0000                                    | 1.0000      |
| 3801               | 9              | 0.0000                                        | 0                           | 0.5833                             | 1.0000                                    | 1.0000      |
| 3803               | 9              | 0.0000                                        | 0                           | 0.5833                             | 1.0000                                    | 1.0000      |
| 3800               | 10             | 0.0000                                        | 0                           | 0.5000                             | 1.0000                                    | 1.0000      |
| 3802               | 11             | 0.0094                                        | 135                         | 0.4167                             | 0.9225                                    | 0.9467      |
| 3721               | 6              | 0.0589                                        | 326                         | 0.8333                             | 0.5120                                    | 0.8714      |
| 3722               | 8              | 0.0516                                        | 31                          | 0.6667                             | 0.5719                                    | 0.9878      |
| 3723               | 9              | 0.0602                                        | 37                          | 0.5833                             | 0.5008                                    | 0.9854      |
| 3724               | 12             | 0.1206                                        | 1688                        | 0.3333                             | 0.0000                                    | 0.3341      |
| 3806               | 7              | 0.0336                                        | 121                         | 0.7500                             | 0.7217                                    | 0.9523      |
| 3807               | 7              | 0.0000                                        | 0                           | 0.7500                             | 1.0000                                    | 1.0000      |
| 3804               | 8              | 0.0344                                        | 487                         | 0.6667                             | 0.7148                                    | 0.8079      |
| 3805               | 4              | 0.0247                                        | 2535                        | 1.0000                             | 0.7952                                    | 0.0000      |
a total length of 15.7 km with more than 50 red lights along the route [16]. Given different driving conditions of different bus routes and the variances in drivers’ driving behaviors, the optimal vehicle brands for different bus routes are also different. For example, among the 10-meter bus, brand B suits the best for Route 134, while brand D suits best for Routes 302 and 646. In addition, for the same bus route, such as Route 134, the best brand among the 10-meter bus is brand B, and the best brand among the 8-meter bus is brand D. The underlying causes of the above problems remain to be explored in the future.

It can also be observed that vehicles of the same brand could have different scores based on the test and evaluation results of Routes 646 and 638, which might be due to different drivers and road conditions in different operating periods. However, the overall difference in the evaluation scores is small, demonstrating the scientific nature of the proposed evaluation method. For those with great differences, such as Bus 3727 and Bus 3728 (both brand C), the main reason for the variation might be that Bus 3728 had several serious failures, and the duration of failure maintenance is much longer than that of Bus 3727. Continuing with long-term road operational tests can help eliminate such scores’ gap caused by such failures.

Besides, road test results delineate that the 8-meter bus of Route 134 has a small difference from Bus 4011 (brand A) and Bus 3806 (brand D) in the scores, while the scores of Bus 3801 (brand B) and Bus 3721 (brand C) are both low and have great differences. It can be assumed that the performance of Bus 4011 and Bus 3806 shows great resemblance. Similar situations above can be observed in other routes. One possible reason is that using the entropy weight method to get the scores can only achieve a macroscopic classification between vehicle brands due to some realistic limitations such as the lack of multi-source data. More microscopic indicators can be incorporated in the future study. For example, the battery electric bus data from Shenzhen and other cities could be further captured and compared with the case of Nanjing. Besides, it should be noted that the aforementioned evaluation results were based on the 50-day road test data of new buses, which were able to reflect the comprehensive performance of a new car, but they did not accommodate the aspect of long-term operating performance such as battery attenuation and maintenance.

### Table 11: Comprehensive evaluation score of battery electric buses in Nanjing.

| Vehicle length (m) | Vehicle number | Reliability Weight 0.4420 | Economy Weight 0.2922 | Security Weight 0.2658 | Total score |
|--------------------|----------------|---------------------------|------------------------|------------------------|-------------|
|                    | 4015           | 0.7897                    | 0.4198                 | 0.8792                 | 0.7054      |
|                    | 4016           | 0.8403                    | 0.2840                 | 0.8792                 | 0.6881      |
|                    | 4017           | 0.7796                    | 0.5169                 | 0.5730                 | 0.6479      |
|                    | 4018           | 0.7189                    | 0.3907                 | 0.5891                 | 0.5885      |
|                    | 3809           | 1.0000                    | 0.3299                 | 0.8792                 | 0.7721      |
|                    | 3808           | 0.9494                    | 0.2911                 | 0.7583                 | 0.7062      |
|                    | 3811           | 0.7849                    | 0.1650                 | 0.8920                 | 0.6322      |
|                    | 3810           | 0.7646                    | 0.3590                 | 0.6778                 | 0.6230      |
|                    | 3725           | 0.0810                    | 0.6798                 | 0.4774                 | 0.3613      |
|                    | 3726           | 0.0607                    | 0.6410                 | 0.7912                 | 0.4244      |
|                    | 3727           | 0.0810                    | 0.9418                 | 0.7418                 | 0.5082      |
|                    | 3728           | 0.0506                    | 0.8447                 | 0.3587                 | 0.3646      |
|                    | 3813           | 0.7704                    | 0.6262                 | 0.8445                 | 0.7479      |
|                    | 3815           | 0.7906                    | 0.4515                 | 0.8152                 | 0.6980      |
|                    | 3812           | 0.6489                    | 0.6165                 | 0.9194                 | 0.7113      |
|                    | 3814           | 0.6894                    | 0.5971                 | 0.9597                 | 0.7343      |

| Vehicle number | Reliability Weight 0.3784 | Economy Weight 0.4497 | Security Weight 0.1719 | Total score |
|----------------|----------------------------|------------------------|------------------------|-------------|
| 4011           | 0.8160                     | 0.5632                 | 0.8493                 | 0.7081      |
| 4012           | 0.8817                     | 0.5121                 | 0.7520                 | 0.6932      |
| 4013           | 0.7503                     | 0.5121                 | 0.6637                 | 0.6283      |
| 4014           | 0.7897                     | 0.5267                 | 0.8282                 | 0.6780      |
| 3801           | 0.5585                     | 0.3406                 | 0.8773                 | 0.5153      |
| 3803           | 0.5322                     | 0.2456                 | 0.8773                 | 0.4627      |
| 3800           | 0.5059                     | 0.2529                 | 0.8527                 | 0.4518      |
| 3802           | 0.5059                     | 0.3114                 | 0.7822                 | 0.4659      |
| 3721           | 0.1051                     | 0.1315                 | 0.7353                 | 0.2253      |
| 3722           | 0.0789                     | 0.0073                 | 0.7487                 | 0.1618      |
| 3723           | 0.0131                     | 0.0000                 | 0.6986                 | 0.1251      |
| 3724           | 0.0657                     | 0.1315                 | 0.2178                 | 0.1215      |
| 3806           | 0.4928                     | 0.9415                 | 0.8126                 | 0.7496      |
| 3807           | 0.4797                     | 0.8977                 | 0.9264                 | 0.7445      |
| 3804           | 0.4534                     | 0.8831                 | 0.7339                 | 0.6949      |
| 3805           | 0.4665                     | 0.8831                 | 0.5709                 | 0.6718      |
### Table 12: Total evaluation score of 10-meter battery electric buses.

| Route | Vehicle Number | Brand Name | Vehicle Length | Total Evaluation Score | Highest Total Evaluation |
|-------|----------------|------------|----------------|------------------------|--------------------------|
| 134 W | 4015 A         | 10490 mm   | 0.7054         |                        |                          |
|       | 3809 B         | 10490 mm   | 0.7721         | √                      |                          |
|       | 3725 C         | 10480 mm   | 0.3613         |                        |                          |
|       | 3813 D         | 10490 mm   | 0.7479         |                        |                          |
| 302 W | 4016 A         | 10490 mm   | 0.6881         |                        |                          |
|       | 3811 B         | 10490 mm   | 0.6322         |                        |                          |
|       | 3726 C         | 10480 mm   | 0.4244         |                        |                          |
|       | 3815 D         | 10490 mm   | 0.6980         | √                      |                          |
| 646 W | 4017 A         | 10490 mm   | 0.6479         |                        |                          |
|       | 4018 A         | 10490 mm   | 0.5885         |                        |                          |
|       | 3808 B         | 10490 mm   | 0.7062         |                        |                          |
|       | 3810 B         | 10490 mm   | 0.6230         |                        |                          |
|       | 3727 C         | 10480 mm   | 0.5082         |                        |                          |
|       | 3728 C         | 10480 mm   | 0.3646         |                        |                          |
|       | 3812 D         | 10490 mm   | 0.7113         |                        |                          |
|       | 3814 D         | 10490 mm   | 0.7343         | √                      |                          |

### Table 13: Total evaluation score of 8-meter battery electric buses.

| Route | Vehicle Number | Brand Name | Vehicle Length | Total Evaluation Score | Highest Total Evaluation |
|-------|----------------|------------|----------------|------------------------|--------------------------|
| 134 W | 4011 A         | 8060 mm    | 0.7081         |                        |                          |
|       | 3801 B         | 8490 mm    | 0.5153         |                        |                          |
|       | 3721 C         | 8045 mm    | 0.2253         |                        |                          |
|       | 3806 D         | 8540 mm    | 0.7496         | √                      |                          |
| 302 W | 4012 A         | 8060 mm    | 0.6932         |                        |                          |
|       | 3803 B         | 8490 mm    | 0.4627         |                        |                          |
|       | 3722 C         | 8045 mm    | 0.1618         |                        |                          |
|       | 3807 D         | 8540 mm    | 0.7445         | √                      |                          |
| 638 W | 4013 A         | 8060 mm    | 0.6283         |                        |                          |
|       | 4014 A         | 8060 mm    | 0.6780         |                        |                          |
|       | 3800 B         | 8490 mm    | 0.4518         |                        |                          |
|       | 3802 B         | 8490 mm    | 0.4659         |                        |                          |
|       | 3723 C         | 8045 mm    | 0.1251         |                        |                          |
|       | 3724 C         | 8045 mm    | 0.1215         |                        |                          |
|       | 3804 D         | 8540 mm    | 0.6949         | √                      |                          |
|       | 3805 D         | 8540 mm    | 0.6718         |                        |                          |
cost. This is also the shortcoming of short-term road operation test evaluation method.

6. Conclusions and Expectations

In order to accurately and objectively evaluate the comprehensive operation ability of different brands of battery electric buses, this paper constructed a comprehensive evaluation framework for battery electric buses. The total evaluation scores of all brands of buses were obtained through the entropy weight method, and the major contributions can be summarized as follows:

(1) Based on the analysis of the current situation of Chinese battery electric buses, the road operation test was selected as the major research method and was combined with quantitative mathematical analysis. The total research flow can be concluded as three steps, i.e., determination of test conditions, data collection, and data analysis.

(2) According to the analysis of the technical and operational characteristics of the battery electric bus and according to the evaluation principles, reliability, economy, and security were determined to be three criteria. The corresponding indexes for selecting the battery electric bus based on the road operation test were also determined.

(3) The entropy weight method was used to establish the evaluation model. The weight of the evaluation indexes and the comprehensive evaluation score of each vehicle were calculated with a study case of 32 battery electric buses. Having compared the evaluation results based on two types of buses from four different brands, the most appropriate bus model was determined.

However, due to the short test period and the absence of subjective factors, there are still some shortcomings. The outlooks of how these shortcomings can be improved and what future works can be done are as follows:

(1) When constructing the comprehensive evaluation system of battery electric buses, it is difficult to collect some subjective index data, which may lead to some deviation between the final total evaluation scores of battery electric buses and the actual situation. This can be solved by expanding the scope of the index system, such as adding the after-sales service indexes and adaptability indexes, which will make the results more accurate.

(2) In the weight calculation of battery electric buses in Nanjing, the entropy weight method relies heavily on the samples, so the weight of each index can be obtained more accurately by increasing the quantity of the samples. By carrying out long-term road test (for example, containing each season), adding road test projects, and combining the traffic flow characteristics in each city, battery electric buses which are more suitable can be better selected in the future.

(3) During the selection process, the battery will decay in daily high-intensity use, so it will bring a significant increase in the use cost in the future. To solve this problem, it is necessary to consider the maintenance costs and the rationality of the supporting charge scheme. Indexes like maintenance cost in subsequent use and differences between charging schemes should be further accommodated in future works.

(4) Bus companies need to have complementary models, so it is necessary to consider how to avoid the problem of single fleet in future studies and applications.

(5) After accumulating a longer period of charge and discharge cycle data, it is possible to carry out battery remaining useful life prediction and uncertain quantification. Then battery lifespan can be taken as an important index when carrying out the vehicle selection process.

(6) In the following studies, based on the road test data, the machine learning tool [37] or the random forest technique [38] can be adopted to determine the feature importance of the battery electric bus.

Data Availability

Data are available on request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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Supplementary Materials

From August 12 to September 30 in 2017, the Nanjing Bus Company conducted a more than one and a half month road test. Daily road operation data collected between August 12 and September 30 in 2017 are shown in the supplementary file 'primary data'. (Supplementary Materials)

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