Evaluation Methods of Electric Buses in Public Transportation: A Review of the Literature

Xiao Li, Balázs Horváth and Ágoston Winkler

Széchenyi István University, Faculty of Architecture, Civil Engineering and Transport Sciences, Egyetem tér 1, 9026 Győr, Hungary, email: li.xiao@sze.hu, hbalazs@sze.hu, awinkler@sze.hu

Abstract: *Public transport provides accessible and affordable mobility for the general public and varies widely across cities and regions due to population density, infrastructure, and governmental policies. With high cost-effectiveness, environmental sustainability and universal accessibility, electric buses support low-carbon urban development for users of all age groups. However, focusing solely on decarbonizing private vehicles is insufficient to achieve efficient urban space management. This paper reviews the recent research progress in evaluation methods for electric bus operations in public transportation. Current studies mainly concentrate on vehicle planning, operational management, and infrastructure development, while research related to Life Cycle Assessment (LCA) remains relatively limited. This review clarifies the characteristics and gaps of mainstream evaluation approaches, enriches the methodological system for electric bus assessment and provides new concepts and theoretical support for the large-scale application and scientific deployment of battery powered electric buses.*

Keywords: LCA; public transport; fleet operation; vehicle scheduling; electric buses

1 Introduction

Public transport provides accessible, affordable, and sustainable mobility services for the general public. It is designed primarily for people without access to private vehicles or those who prefer low-carbon travel. Public transport systems differ significantly across cities and regions, affected by population density, infrastructure conditions, and government policies. With high cost-effectiveness, environmental sustainability, and universal design, electric buses are suitable for users of all age groups and have become a core component of modern urban transport systems. However, focusing only on reducing carbon emissions from private vehicles is not sufficient to achieve efficient urban space management and low-carbon development goals. Therefore, promoting the electrification of public transport, especially the large-scale application of electric buses, is of great practical importance.

In recent years, driven by technological progress and supportive policies, electric buses have been widely deployed worldwide. Compared with traditional diesel buses, electric buses eliminate tailpipe emissions, reduce urban air pollution, lower dependence on fossil fuels, and improve the efficiency of the energy system [1]. Nevertheless, large-scale promotion still faces practical challenges, including high upfront investment, limited driving range, long charging time, insufficient supporting infrastructure, and complex operational scheduling. In this context, scientific and systematic evaluation methods are essential for fleet planning, route design, energy management, and policy decision-making. Current studies mainly focus on vehicle planning, operation scheduling, and infrastructure configuration, while systematic reviews of unified evaluation frameworks—especially those integrating life cycle thinking—remain insufficient.

Against the background of global urbanization and low-carbon transition, it is far from enough to only reduce emissions from private vehicles to achieve high-efficiency urban space management. Public transport electrification represents a more systematic and scalable solution. This paper focuses on evaluation methods for electric bus systems in public transportation, covering fleet operation, vehicle scheduling, resource allocation, energy consumption prediction, and LCA.

1.1 Research Background

The implementation of electric buses has the potential to bring about a multitude of advantages for urban areas and overall sustainability initiatives. To begin, electric buses do not produce any emissions from their tailpipes, which results in a considerable reduction in air pollution and an improvement in the quality of air in urban areas. This dedication to more environmentally friendly modes of transport is in line with broader sustainability objectives, demonstrating leadership in the field of environmentally friendly transport [2]. Additionally, the transition to electric buses help decrease society's dependence on limited oil resources, while simultaneously enhancing the operational efficiency of the power grid. Consequently, this enhances the overall sustainability of the energy system, advocating for a more ecologically conscientious approach to public transportation.

Cities and governments that prioritize the integration of electric buses into their transportation systems convey a resounding message regarding their dedication to emission reduction, air quality enhancement, and the pursuit of a low-carbon future. Energy consumption is sensitive to bus service type, ranging widely between 2 and 4.6 kWh/km, and intercity buses require the largest battery size (320–680 kWh) [3]. Scholars like Moataz Mahmoud and others conducted thorough analyses of each technology's economic, operational, energy, and environmental characteristics on the basis of simulated models and operational data supplied by academics in various settings by means of a thorough review of the performance traits of the three varieties of electric buses (hybrid, fuel cell and battery). Considering general energy efficiency under the assumption of total cost of ownership (TCO) in line with market trends reveals that, although lowering greenhouse gas emissions, pure electric buses are the most appealing solution. It calls for an associated charging infrastructure even if it costs up to 52.1% more than a regular diesel bus. Pure electric public transport's renewable energy electricity has drastically cut energy consumption (50%) and greenhouse gas emissions (98.4%) [4].

1.2 Global Application and Challenges of Electric Buses

At the moment, a great number of nations and municipalities all over the world are actively advocating for the implementation of electric buses as an essential technique to tackle the growing problem of hazardous air pollution. With the largest electric bus fleet on the entire planet, China is a recognized pioneer in this endeavor and represents a significant leader in the field. The United States, on the other hand, managed to sell fewer than 10,000 electric buses in 2016, which is a startling contrast to the fact that China sold more than 120,000 electric buses in 2016 [5].

As a way to ensure the sustainable expansion of the policy-driven battery electric vehicles sector, particularly electric buses, it is imperative to address numerous sustainability issues. The implementation of electric vehicles technology faces substantial obstacles at both the national and industrial scales [6]. These issues encompass inadequate infrastructure, costly power batteries, restricted driving range, and a lack of consumer enthusiasm for purchasing. The sector is facing obstacles like as high cost, slow progress in basic battery technology, and low market demand. As a result, multiple car manufacturers are decreasing or altering their goals for adopting electric power.

Volánbusz, the prominent bus operator in Hungary, is now in the process of significantly increasing its collection of electric buses in line with the nation's wider sustainability initiatives. This expansion is set to be completed by 2024. Volánbusz currently operates over 100 electric buses in multiple Hungarian cities, such as Budapest, Székesfehérvár, Zalaegerszeg, Győr, Eger, Szolnok, and Szeged. This fleet makes a substantial impact on reducing carbon emissions, resulting in the removal of roughly 5,500 tons of CO_2 per year. This reduction is equivalent to the emissions produced by nearly 2,000 passenger cars [7].

Due to the constraints imposed by the current state of battery technology, electric vehicles often have certain intrinsic disadvantages [8]. These include a limited driving range and longer charging times, which make them less competitive for long-distance travel compared to traditional vehicles powered by internal combustion engines. However, the distinct features of urban buses, such as set routes, predetermined distances, and established operating hours, differentiate them from other modes of transportation. On the other hand, suburban routes frequently depend on traditional internal combustion engines or hybrid vehicles. The period of inactivity between operations or while a vehicle is not in use provides a perfect chance for recharging, making public transport an excellent choice for electrification.

1.3 Research Objectives and Scope

Against the background of global urbanization and low-carbon transition, this paper focuses on evaluation methods of electric bus systems in public transportation [9]. It reviews research progress in fleet operation, vehicle scheduling, resource allocation optimization, energy consumption prediction and life cycle assessment (LCA), with the following objectives:

- To systematically summarize the characteristics, application scenarios, and limitations of mainstream electric bus evaluation methods;
- To identify research gaps in current studies, especially the insufficient integration of LCA, data-driven methods, and comprehensive evaluation;
- To provide a methodological reference and theoretical support for the planning, operation, and sustainable development of electric bus systems.

2 Current Research Methods

As urban space management requires integrated and systematic low-carbon strategies, merely decarbonizing private vehicles is insufficient to achieve overall efficiency. In response, this section systematically reviews and analyses typical evaluation methods applied to electric bus operations. Existing studies have verified the effectiveness of multiple tools and indicators, including fleet operation optimization, bus route design, vehicle scheduling schemes, resource allocation, energy consumption analysis, and environmental impact assessment.

Some evaluation approaches focus on the operational performance of bus systems, while others concentrate on vehicle-level performance, environmental footprints, and energy-related impacts [10]. A few studies attempt to establish multi-dimensional comprehensive evaluation frameworks. By summarizing these methods, this paper clarifies their application scenarios, advantages, and limitations, so as to provide a clear methodological basis for the optimization and decision-making of electric bus systems.

To ensure the comprehensiveness, representativeness and reliability of this review, a strict and standardized literature selection process was adopted [11]. The relevant literature was retrieved from high-quality academic databases, including Web of Science, Scopus, Google Scholar, and ScienceDirect. The search timeframe was set in 15 years to focus on recent advances and practical achievements in electric bus evaluation methods. This strict literature selection process ensures the transparency, academic rigor, and credibility of this review, and provides a solid foundation for the following analysis and summary.

The main search terms included electric bus, battery electric bus, public transport, evaluation method, assessment, fleet operation, vehicle scheduling, energy consumption, and life cycle assessment. During the screening process, only English peer-reviewed journal articles and high-quality international conference papers focusing on evaluation frameworks, optimization methods, indicator systems, and empirical analyses related to electric buses were retained. Studies purely concerning battery technology, motor design, material science, or non-academic documents such as reports, news articles, and promotional materials were excluded. This standardized and traceable procedure ensures the reliability of this literature review and provides a solid foundation for the systematic summary of electric bus evaluation methods.

2.1 Fleet Operation

Electric buses, propelled by fuel cells or rechargeable batteries, are increasingly becoming popular worldwide, especially in urban and suburban areas. Over time, they prove to be economically beneficial, even though their initial upfront costs are higher compared to those of fossil fuel alternatives [12]. The effective range of electric buses depends on various elements, such as battery capacity, route circumstances, passenger load, and other influencing factors. It often includes an enhanced noise, vibration and harshness (NVH), is more environmentally friendly, and has reduced operating expenses. However, pure electric buses do have certain drawbacks. Consider the following challenges associated with electric buses:

- **Higher Initial Costs**: Electric vehicles often come with a higher upfront price tag compared to their conventional counterparts.
- **Limited Range and Charging Infrastructure**: The range of electric vehicles can be limited, and access to charging infrastructure may not be as widespread in certain areas.
- **Charging Time**: Charging an electric vehicle can take longer than refueling a conventional vehicle with gasoline or diesel.
- **Battery Weight and Space Constraints**: Electric vehicles batteries can be heavy and take up valuable space within the vehicle, affecting design and cargo capacity.
- **Upgrades and Technological Advancements**: As electric vehicle technology evolves rapidly, staying up-to-date with the latest advancements and upgrades can be a consideration for owners and operators.

Transportation scholars have conducted numerous studies examining the operation of fully electric buses. In the work of Shyam S.G. Perumal et al., an investigation into the operational methodology of electric buses, taking into account charging facilities and charging times, revealed that an optimized charging scheme can yield electricity cost reductions of up to 18% [13]. Jinwoo Lee et al. conducted a study on the cost-effective planning of electric bus systems by examining the trade-offs between fleet size and charging infrastructure capacity. Their empirical analysis underscores the compelling economic and environmental benefits associated with the electrification of bus routes.

In a study led by Wenwei Zhang, Hui Zhao, and their team, numerical experiments were conducted on a linear bus route. The findings revealed that the advantages of the strategy diminish with longer operating cycles [14], primarily because extended cycles necessitate larger batteries to sustain fleet operations. Furthermore, it was observed that there exists a peak demand pattern, whereby the benefits of the strategy transition from positive to negative as the operating cycle duration increases. In the coming years, we will continue to grapple with various challenges, including fleet operations, energy management, sustainability, vehicle technology, and battery technology, as we strive to effectively tackle these issues.

Bus companies' priorities reducing both the overall number of trips and the fleet size, while passengers' concerns center around minimizing waiting times and overcrowding. Striking a harmonious balance between these two interests takes precedence in the realm of bus operation scheduling. The crux of bus operation scheduling lies in the execution of prudent scheduling strategies and the application of sound, evidence-based scheduling methods. The primary goal is to attain the optimal synchronization between capacity allocation and departure times across various routes [15]. A profound comprehension of public transport operations within the transportation sector is indispensable for effective management of public transport services. Such understanding plays a pivotal role in upholding a superior standard of service quality and performance, thereby promoting public transport as the preferred mode of transportation for individuals.

Wang He [16] and other researchers have undertaken thorough investigations in the field of operational research, specifically focusing on the study and evaluation of bus passenger flow. These studies have used large datasets to provide deep insights. These studies apply existing methods for collecting and processing data from conventional buses. The main objective is to analyses important information inside the bus data structure in order to evaluate passenger flow and bus operations. Also, they present frequently employed data mining techniques. They delve deep into the analysis of three specific bus routes, examining passenger flow along the route, during various time periods, and at station cross-sections. The findings highlight the need for the bus operations department to make strategic adjustments in terms of the number and speed of shuttle buses based on route-specific passenger flows and different time periods. These recommendations aim to enhance the overall efficiency of bus operations and elevate service quality.

Zheng Shuqing [17] and a group of Chinese scholars conducted a comprehensive study on the cost regulation of urban public transport, concentrating on situations where public transport enterprises lack fare control and rely on government financial subsidies to sustain their daily operations. Grounded in the fundamental principles, attributes, and implications of cost regulation theories, their research defines the parameters encompassing regulatory costs and regulatory revenues within the framework of public transport cost regulation. The study distills the accounting methods currently employed for regulating costs in various cities' cost regulation schemes and formulates an accounting model. Additionally, the authors introduce the standard cost method as an innovative approach for accounting for regulatory costs.

Kühne et al. [18] highlight that the operational design of contemporary electric trolleybuses, which utilize electricity, addresses the limitations of conventional fossil-fuel-powered buses by incorporating features such as regenerative braking and energy storage through advanced supercapacitors. Electric bus systems fulfill environmental standards while providing significant economic efficiency, rendering them a viable strategy for advancing urban transportation planning towards sustainable future technologies. Additionally, the article carefully examined the assessment methodology used to evaluate the efficiency and service quality of public transport firms. This involved examining the key components, evaluation methods, and calculation of indicators in each of these assessment systems. Additionally, it established a correlation between the results of the assessment system for operational efficiency in public transport companies and the distribution of subsidies for cost regulation. Based on these discoveries, the authors suggested a change in government operations to achieve enhanced visibility, quantifiability, and manageability. This move would act as a spur for businesses to prioritize improvements in the efficiency of public transport operations and service standards, while also examining the results of their operational efforts.

In addition, many studies have explored evaluation systems for operation efficiency and service quality of public transport enterprises, including index composition, evaluation methods, and calculation methods. These studies link evaluation results with subsidy allocation and suggest that government management should be more transparent, quantifiable, and controllable, encouraging enterprises to improve operation efficiency and service levels.

2.2 Bus Route Optimization and Vehicle Scheduling

Numerous cities have embraced advanced intelligent bus operation management systems. These systems offer real-time monitoring and analysis of various critical data points, including bus vehicle operations, driver status, and passenger travel patterns. This wealth of information empowers the public transport sector to make precise and informed operational decisions, ultimately enhancing the efficiency and service quality of public transportation. In addition to real-time insights, the intelligent bus operation management system plays a crucial role in monitoring and tracking bus vehicle maintenance [19].

It also aids bus companies in effectively managing and consolidating data related to vehicles, passengers, drivers, and more, facilitating the generation of comprehensive data reports. Route-based bus operations are the standard in the majority of public transport systems globally. These operations require a meticulous coordination of vehicle assignments and staffing with customized routes suited to meet their distinct needs.

A widely recognized methodology for route design, pioneered by Avishai Ceder, Nigel H.M. Wilson [20], and others in their 1986 study, involves a systematic approach. Initially, potential viable routes are identified, considering various factors such as travel time, route length, stopping points, and transport costs to assess their feasibility. Subsequently, these potential routes are scrutinized against the existing road network to ensure compatibility. These selected routes must not overlap with existing routes, accounting for the placement of current stops and areas to be served.

For each viable route, further optimization is conducted to enhance operational efficiency and reduce costs. This optimization process takes into account factors like passenger demand, network congestion, and service times, resulting in a well-thought-out and streamlined bus route system. Ultimately, the optimal route is chosen following the aforementioned steps, striving to strike a balance between the interests of passengers and operators to achieve an optimal bus route network design. It is important to emphasize that this algorithm is only a part of the larger bus operations planning process and does not include the whole bus network design.

Recognizing the intricate complexities of real-world road traffic environments, scholars like Ali M. Abdelfattah [21] have developed a model tailored to predict bus delay times. While current bus tracking technology can furnish real-time bus location data, there remains a need for refining the forecasting of bus travel times from the last observed point to the final destination, especially in mixed traffic scenarios. This predictive model integrates microsimulation using VISSIM software and field research, encompassing a comprehensive array of factors influencing bus travel speeds. These factors include variables such as traffic flow, vehicle density, lane count, traffic signals, and vehicular maneuvers like turns. As a result, the model can make accurate predictions under both standard traffic conditions and temporary lane closures, thereby offering robust support for actual bus arrival time information.

Finally, bus route optimization and vehicle scheduling form the core of electric bus operational planning. Existing methods effectively improve route rationality, arrival time accuracy, and resource utilization by combining network design algorithms, traffic simulation, and real-time monitoring techniques. However, most approaches focus on traditional operational objectives and rarely integrate energy consumption characteristics, battery degradation, charging constraints, or life cycle environmental impacts into the scheduling process.

2.3 Optimizing Resource Allocation

Several of the study approaches stated above lack precision in terms of vehicle classification, which could result in discrepancies between theoretical predictions and actual operating situations. Antti Lajunen [22] developed a specialized simulation tool to examine and evaluate the energy usage and overall expenses of electric buses on different routes. The life cycle cost of an electric bus is mostly determined by the original purchase cost of the bus and the charging equipment that comes with it. Furthermore, while evaluating various charging techniques, the energy capacity of the battery system, especially during evening charging, becomes a crucial determinant for the everyday functioning of electric buses. Surprisingly, the energy consumption and life cycle costs of fast-charging electric buses are not much affected by the size of their batteries. On average, the prices of fast-charging electric buses are approximately 7% higher than the expenses of their diesel counterparts. This finding highlights the complexity of achieving substantial reductions in carbon emissions by the mere substitution of conventional combustion engine-powered buses.

In addition, a number of academics have conducted optimize studies that have focused on scheduling, taking into account the operation modes of a variety of different vehicles [23]. These studies have also included organizational management and optimization's that are specifically tailored to the operations of electric buses. Ultimately, the objective of these projects is to contribute to a strategy that is more nuanced and efficient in contrast to the incorporation of electric buses. This will be accomplished by resolving discrepancies in transport capacity and unit energy consumption that exist across different types of vehicles.

Electric vehicles are on the verge of achieving economic equivalence with conventional fuel-powered vehicles in the near future. Although reducing emissions from private automobiles is important, it is not sufficient on its own to provide a comprehensive solution for good urban spatial management. Investing in the development and implementation of electric bus technology directly and significantly improves the overall quality of urban life.

Future research endeavors centered on electric buses will priorities sustainability, encompassing economic, environmental, and service quality dimensions. Additionally, there will be a notable emphasis on optimizing energy management strategies and refining fleet operations to ensure the continued progress and efficiency of electric bus systems.

Valentina Conti [24] and other researchers harnessed the power of a Decision Support System (DSS) to meticulously assess electrification options for a specific bus route. Their evaluation involved a thorough comparison of investment, management costs, and external expenses attributable to vehicle emissions and noise, juxtaposed against traditional alternatives such as compressed natural gas and diesel. As an illustrative example, the DSS methodology was applied to multiple bus routes within the southwestern region of Rome, Italy. These routes encompassed peripheral, primary connections from the city outskirts to the urban core, and secondary routes serving major metro stations. This extensive analysis aimed to affirm the technical feasibility of diverse electrification strategies. The findings unequivocally demonstrate that for each of these routes, a suitable electrification solution can be identified, all while maintaining a total cost that is either lower than or on par with that of conventional alternatives.

Owing to the unique characteristics of electric buses, their operational strategies must hinge on maintaining an adequate surplus of power. Simultaneously, in light of economic considerations, most companies refrain from wholesale replacement of their fleets with exclusively electric options. Consequently, various researchers have embarked on studies aimed at optimizing vehicle configurations.

For instance, LI Lu [25] and colleagues introduced a fleet optimization management model that accounts for full life cycle cost-effectiveness. This model incorporates variables representing pure electric, hybrid, fuel oil, and natural gas buses, all while considering budgetary constraints.

Meanwhile Zhou Bin [26] and other researchers have specifically examined limitations concerning the range of cars and the time it takes to charge them. As a result, they have created a scheduling model for pure electric buses that aims to minimize the number of vehicles needed and the lengths they travel when idle. A further significant contribution is made by An Kun [27], who developed an optimal model to strategically arrange charging stations and determine the fleet size in an electric bus system. The main goal is to reduce the overall costs associated with the building of charging stations, acquiring a fleet, charging expenses, and other relevant variables.

A paradigm that connects real vehicle performance, the dependability of urban bus services, battery capacity, and charging infrastructure to the viability of bus electrification was created by Gao et al. [28]. According to their study, electric buses may attain the same level of service dependability as traditional buses by experimenting with different battery capacity and charging techniques on different routes. The study also points out that battery size may be drastically decreased and time delays brought on by prolonged charging sessions can be avoided by performing brief, sporadic top-up charges at specified bus stops. Additionally, using a variety of battery types and adaptable battery swapping techniques might result in considerable cost reductions while guaranteeing that electric buses can adjust to various urban driving patterns.

Fei et al. [29] examined a novel revenue model—the “Bus-to-Grid” (B2G) or “E-Buses as Power Storage” (EBaPS) concept—enabling electric buses to offer services to the power grid concurrently with transit services. Bus operators may engage in two categories of contracts with the grid. The initial concept is "Sale by Market Price" (SbMP), which posits that buses can generate and sell electricity at prevailing real-time market pricing. The second is "Frequency Control Reserve" (FCR), wherein buses discharge electricity in reaction to instantaneous demands from the grid. This strategy creates new revenue prospects for operational companies.

In summary, existing evaluation methods for electric bus systems have formed a relatively comprehensive system covering fleet operation, route scheduling, and resource allocation. Most studies focus on operational efficiency, cost optimization [30], and technical feasibility [31], providing strong support for the planning and management of electric bus projects. However, most evaluation approaches are still limited to the operational stage, and few studies integrate life cycle thinking, dynamic energy consumption characteristics, and data-driven technologies into a unified framework. In addition, the coordination and trade-off among economic, environmental, and service quality objectives have not been fully addressed. These limitations reveal important directions for the future development of electric bus evaluation systems, which will be further discussed in the following sections.

3 Trend and Future

The review of electric bus systems has progressively transitioned from a singular focus on operational optimization to a multifaceted holistic evaluation. Early studies mainly focused on technical feasibility, fleet scheduling, route planning, and cost–benefit analysis, which laid a solid foundation for the practical operation of electric bus projects. With the deepening of global low-carbon transition and the refinement of urban transportation management, research perspectives are shifting toward long-term sustainability, full-process impact quantification, and data-driven intelligent decision-making. However, most existing evaluation methods still focus on the operational stage, while systematic integration of the whole life cycle, dynamic energy consumption characteristics, and coordinated optimization of multiple objectives remains insufficient. In view of these trends and gaps, this section focuses on three key directions with high academic and practical value: life cycle assessment [32], energy consumption modeling, and data-driven intelligent decision-making. And further prospects future research priorities for electric bus evaluation systems.

3.1 Life Cycle Assessment

Life Cycle Assessment is not a new research field and has been widely adopted in environmental impact analysis of transportation systems. For example, Kawamoto et al. [33] used LCA methodology to conduct a comparative analysis of CO2 emissions encompassing conventional petrol and diesel-fueled vehicles versus prominent alternative powertrains, namely electric vehicles. Their analysis considered various phases, including vehicle manufacturing, fuel extraction, refining, power generation, and end-of-life considerations.

The concept of Life Cycle Assessment was introduced by The Coca-Cola Company in 1969, originally created as an environmental management tool in the United States [34]. The company undertook its first documented LCA to assess the environmental effects of various packaging materials, such as glass bottles, plastic bottles, and aluminum cans. This was an initial step taken to tackle the issue of packaging waste.

Over time, the car industry gradually adopted the LCA evaluation process, just like other sectors. Interestingly, the research revealed that electric vehicles exhibit higher life-cycle CO2 emissions when contrasted with traditional internal combustion engine vehicles [35]. This discrepancy primarily stems from the elevated CO2 emissions associated with battery production incorporated into the assembly process. Nevertheless, in locales where renewable energy sources and low CO2-emitting electricity generation are widespread, electric vehicles demonstrate a lower overall operational CO2 footprint, particularly as their lifespan increases. It is worth noting that the carbon emissions arising from battery replacement after a certain mileage threshold must not be disregarded.

Researchers such as Girardi conducted a comparable study, utilizing Italy as an illustrative example. Although there are several comparative LCA available, only a few focuses explicitly on evaluating the electricity sources used for charging electric vehicle batteries. Girardi's analysis reveals that, in the context of the Italian electrical grid, electric vehicles have a reduced environmental impact compared to internal combustion engine vehicles [36].

It's important to note that the manufacturing and operational contexts of fully electric buses diverge significantly from those of passenger cars, which suggests the potential for further in-depth research within the realm of LCA for this specific subdomain. Many studies within the domain of LCA typically commence from the perspectives of environmental and energy considerations. For instance, Hernandez et al. [37] conducted research that delineated the environmental and energy resource implications of various electric powertrain components throughout their lifecycle. Their work dissected the impact of non-energy and energy resource depletion associated with production, utilization and management of electric drive systems.

Potkány et al. [38] have shown that the total lifecycle costs of electric buses may be comparable to those of diesel buses; however, due to disparities in operating conditions and fluctuations in maintenance and energy expenses, the cost structure of electric buses presents considerable advantages, especially in the long term. Moreover, with technology improvements and regulatory endorsement, electric buses possess additional possibilities regarding economic efficiency and environmental impact.

However, few LCA studies consider the complexity of fleet configuration, which is still a relatively under-explored field. In addition, traditional LCA often ignores the importance of energy use and management, or treats them as separate parts. When combined with LCA, energy consumption becomes a key indicator for fleet structure evaluation and optimization.

3.2 Energy Consumption

On the basis of life cycle evaluation, energy consumption has become one of the most direct and critical indicators to measure the operational efficiency and environmental performance of electric buses. The consumption of energy by vehicles, which serves as an essential measure of whether or not a vehicle is friendly to the environment, has also emerged as a major research issue in the modern day.

Researchers such as Abdelaty et al. [39] have contributed to this discourse, relying on the intricate relationship between energy consumption and battery electric buses. Their research highlights the multifaceted factors affecting electric buses energy consumption, encompassing vehicle characteristics, operational practices, network topology, and external variables. The multifarious nature of these factors makes predicting energy consumption challenging. To tackle this issue, the authors have developed and compared several data-driven modeling techniques, incorporating machine learning and statistical models. These models are constructed using a comprehensive factorial design of experiments, involving a large dataset (n = 907,199), validated through a Simulink energy simulation model. Subsequently, they employ a separate test dataset (n = 169,344), to make predictions regarding energy consumption.

Y. Chen [40] and other researchers have undertaken data-driven modeling and estimation of energy consumption in electric buses operating under actual driving conditions. In this study, they harnessed Long Short-Term Memory and Artificial Neural Network techniques to facilitate real-time prediction of energy consumption. Additionally, the research introduced a data partitioning algorithm designed to distinguish between energy charging and discharging modes.

Also, Pengshun Li [41] and a group of academics proposed a new prediction method for electric bus energy consumption. This method combined stochastic speed profile generation and data-driven technology to improve prediction accuracy and reduce response time. They further used kNN and RF models to replace the stochastic generation module, aiming to improve prediction stability with an increasing number of operating records. This study provides a practical tool for real-time management and scheduling of large-scale electric bus systems for cities.

The energy consumption evaluation has shifted from traditional statistical analysis to data-driven intelligent prediction. Existing models have achieved high accuracy in estimating energy use under real-world conditions. However, most studies focus on single-route or single-vehicle scenarios, while integrated energy consumption evaluation that combines fleet scale, route network, and real-time traffic remains limited. The integration of energy consumption analysis with life cycle assessment and operational scheduling will be important for refined electric bus management.

3.3 Data-driven Intelligent and Decision-making

With the rapid development of big data, artificial intelligence, and intelligent transportation systems, data-driven intelligent decision-making has become an emerging and critical direction in electric bus evaluation and operation management. Massive real-world data generated from vehicle terminals, charging facilities [42], passenger records enables more accurate, dynamic, and scenario-adaptive evaluation. Compared with traditional model-based methods, data-driven approaches can capture complex nonlinear relationships among vehicle status, route conditions, energy consumption, and operational efficiency, thereby supporting refined scheduling, predictive energy management, and personalized service optimization. This paradigm shift highlights the necessity of incorporating intelligent algorithms and real-time data analytics into the life cycle and energy consumption [43] evaluation of electric buses.

Lin [44] and colleagues integrate business chain cases and multi-source operational data to construct a data-driven optimization framework. It establishes a mathematical model for public transport departure scheduling with the goal of optimizing the comprehensive operational cost, and introduces an enhanced quantum genetic algorithm (EQGA) to solve the model. The empirical results show that this hybrid-driven optimization mode can effectively balance the interest demands of multiple parties, and has stronger global search capability and solution stability compared with traditional intelligent optimization algorithms, which can provide a new technical idea and engineering reference for the dynamic operation and scheduling optimization of urban intelligent public transport.

The seminal study by Sennefelder et al. [45] demonstrates that ML-driven approaches are not only theoretically feasible but also practically implementable. Their research, which integrates model predictions with a Django-based web application, highlights the translational value of data-driven solutions from the laboratory to the operational dashboard. This work is particularly relevant for the current research, as it validates the utility of ML algorithms for processing high-dimensional vehicular data. Specifically, this literature review contextualizes the proposed methodology within the state-of-the-art, emphasizing the need for robust feature selection—such as speed profiles and passenger load—and provides a foundation for comparing the performance of the proposed model against established benchmarks.

Tian et al. [46] proposed a data-driven hierarchical control framework. Recognizing that conventional rule-based strategies often yield suboptimal fuel economy while global optimization methods such as dynamic programming (DP) are computationally prohibitive for online applications, the authors developed a two-layer architecture that leverages historical optimal control data and real-time route information. The upper layer performs SOC reference trajectory planning by learning from globally optimal DP results, while the lower layer executes real-time power allocation between the engine and electric motor to track the planned SOC profile. Validated under real-world urban bus driving cycles, the proposed strategy not only achieves fuel consumption significantly closer to the global optimum than traditional charge-depleting/charge-sustaining (CD-CS) strategies, but also maintains low computational complexity suitable for online vehicle control. The results demonstrate that data-driven hierarchical control can effectively balance energy efficiency, adaptability to varying driving conditions, and real-time performance for fixed-route hybrid electric buses.

Overall, data-driven methods significantly improve the accuracy, timeliness, and adaptability of electric bus evaluation and control. Machine learning, multi-source data fusion, and hierarchical control have been successfully applied to scheduling, energy management, and operational optimization. Nevertheless, challenges remain in model interpretability, cross-scenario generalization, and real-time performance under large-scale fleet conditions. Future research will further integrate edge computing, digital twins, and multi-objective optimization to build more complete and reliable intelligent decision systems.

4 Conclusions and Prospects

This paper systematically reviewed the evaluation methods for electric bus systems in public transportation. It covered fleet operation, route optimization, vehicle scheduling, resource allocation, energy consumption modeling, life cycle assessment and data-driven, intelligent decision-making. Based on extensive literature analysis, core conclusions can be drawn in the following paragraphs.

First, current evaluation research has formed a relatively complete system focusing on operational efficiency, cost optimization, and technical feasibility. Studies on fleet scale design, charging strategy, route planning, delay prediction, and resource allocation have provided solid methodological support for the planning and operation of electric bus projects.

Second, most existing evaluation methods are limited to the operation stage of electric buses, while comprehensive research integrating full life cycle thinking (including production, usage, and recycling), dynamic energy consumption features, and multi-objective coordination is insufficient. In particular, studies combining LCA with fleet configuration, scheduling, and economic evaluation remain limited.

Third, data-driven methods represented by machine learning, multi-source data fusion, and hierarchical control have been gradually applied to energy consumption prediction and operation optimization, significantly improving the accuracy and adaptability of evaluation. However, model interpretability, real-time performance, and cross-scenario generalization still need to be enhanced.

Fourth, the cost difference between electric buses and diesel buses is gradually narrowing. With the support of renewable electricity, the environmental advantages of electric buses are increasingly significant. Nevertheless, constraints such as battery performance, charging infrastructure, and operational strategy design still restrict the large-scale and high-efficiency application of electric buses.

According to the current research status and development trends, future research directions are prospected as follows:

- To strengthen full life cycle evaluation covering vehicle production, operation, battery replacement, and recycling, and establish a unified LCA framework for electric bus fleets.
- To integrate energy consumption prediction, LCA, and operational scheduling into a multi-objective optimization model, realizing the coordinated optimization of economy, environment, and service quality.
- To develop more robust and interpretable data-driven models suitable for large-scale bus networks, and realize real-time intelligent decision-making combined with edge computing and digital twin technology.
- To carry out more localized and scenario-oriented evaluation studies considering regional differences in policies, electricity structures, climate conditions, and operation characteristics.
- To explore innovative models such a supercapacitor power, battery swapping, and flexible fleet scheduling to improve operational economy and sustainability.

This review clarifies the characteristics, application scenarios and limitations of mainstream electric bus evaluation methods. It identifies key research gaps, and provides a methodological reference and theoretical support for researchers, operators, and policymakers to promote the scientific, efficient, and sustainable development of urban electric bus systems.

References

[1] M. Gallo and M. Marinelli, “Sustainable Mobility: A Review of Possible Actions and Policies,” *Sustainability-basel*, vol. 12, no. 18, Art. no. 18, Jan. 2020, doi: 10.3390/su12187499.

[2] J. A. Manzolli, J. P. Trovão, and C. H. Antunes, “A review of electric bus vehicles research topics – Methods and trends,” *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112211, May 2022, doi: 10.1016/j.rser.2022.112211.

[3] H. Basma, C. Mansour, M. Haddad, M. Nemer, and P. Stabat, “Energy consumption and battery sizing for different types of electric bus service,” *Energy*, vol. 239, p. 122454, Jan. 2022, doi: 10.1016/j.energy.2021.122454.

[4] M. Mahmoud, R. Garnett, M. Ferguson, and P. Kanaroglou, “Electric buses: A review of alternative powertrains,” *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 673–684, Sep. 2016, doi: 10.1016/j.rser.2016.05.019.

[5] O. Olsson, A. Grauers, and S. Pettersson, “Method to analyze cost effectiveness of different electric bus systems,” presented at the 29th World Electric Vehicle Symposium and Exhibition (EVS 2016), June 19-22, 2016, Montreal, Canada, 2016, pp. 604–615. Accessed: Oct. 03, 2023. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-32722

[6] K. Y. Bjerkan, T. E. Nørbech, and M. E. Nordtømme, “Incentives for promoting Battery Electric Vehicle (BEV) adoption in Norway,” *Transportation Research Part D: Transport and Environment*, vol. 43, pp. 169–180, Mar. 2016, doi: 10.1016/j.trd.2015.12.002.

[7] “Volánbusz Completes Green Bus Project | Diplomacy & Trade.” Accessed: Mar. 28, 2026. [Online]. Available: https://dteurope.com/sustainability/volanbusz-completes-green-bus-project/

[8] J.-Q. Li, “Battery-electric transit bus developments and operations: A review,” *Int J Sustain Transp*, vol. 10, no. 3, pp. 157–169, Mar. 2016, doi: 10.1080/15568318.2013.872737.

[9] M. A. Saif, M. M. Zefreh, and A. Torok, “Public Transport Accessibility: A Literature Review,” *Periodica Polytechnica Transportation Engineering*, vol. 47, no. 1, pp. 36–43, 2019, doi: 10.3311/PPtr.12072.

[10] J. A. Manzolli, J. P. Trovão, and C. H. Antunes, “A review of electric bus vehicles research topics – Methods and trends,” *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112211, May 2022, doi: 10.1016/j.rser.2022.112211.

[11] A. Grewal, H. Kataria, and I. Dhawan, “Literature search for research planning and identification of research problem,” *Indian J Anaesth*, vol. 60, no. 9, p. 635, Sep. 2016, doi: 10.4103/0019-5049.190618.

[12] M. Mahmoud, R. Garnett, M. Ferguson, and P. Kanaroglou, “Electric buses: A review of alternative powertrains,” *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 673–684, Sep. 2016, doi: 10.1016/j.rser.2016.05.019.

[13] S. S. G. Perumal, R. M. Lusby, and J. Larsen, “Electric bus planning & scheduling: A review of related problems and methodologies,” *European Journal of Operational Research*, vol. 301, no. 2, pp. 395–413, Sep. 2022, doi: 10.1016/j.ejor.2021.10.058.

[14] W. Zhang, H. Zhao, and M. Xu, “Optimal operating strategy of short turning lines for the battery electric bus system,” *Communications in Transportation Research*, vol. 1, p. 100023, Dec. 2021, doi: 10.1016/j.commtr.2021.100023.

[15] O. J. Ibarra-Rojas, F. Delgado, R. Giesen, and J. C. Muñoz, “Planning, operation, and control of bus transport systems: A literature review,” *Transport Res B-meth*, vol. 77, pp. 38–75, Jul. 2015, doi: 10.1016/j.trb.2015.03.002.

[16] Wang He, “Research on Bus Passenger Flow Analysis and Bus Operation Evaluation Based on Big Data,” Master’s Thesis, Lanzhou Jiaotong University, GANSU, China, 2018. Accessed: Mar. 28, 2026. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201901&filename=1018238119.nh

[17] Zheng Shuqing, “Research on Urban Public Transportation Cost Regulation——Case Study in Guilin,” Master’s Thesis, Guilin University of Electronic and Technology, GUANGXI, China, 2019. Accessed: Mar. 28, 2026. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201902&filename=1019919654.nh

[18] R. Kühne, “Electric buses – An energy efficient urban transportation means,” *Energy*, vol. 35, no. 12, pp. 4510–4513, Dec. 2010, doi: 10.1016/j.energy.2010.09.055.

[19] Mao Lin, “Research on the Evaluation Method of Intelligent Public Transport Scheduling,” Doctor’s Thesis, Southeast University, FUJIAN. China, 2018. Accessed: Mar. 28, 2026. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CDFD&dbname=CDFDLAST2019&filename=1019650000.nh

[20] A. Ceder and N. H. M. Wilson, “Bus network design,” *Transportation Research Part B: Methodological*, vol. 20, no. 4, pp. 331–344, Aug. 1986, doi: 10.1016/0191-2615(86)90047-0.

[21] A. M. Abdelfattah and A. M. Khan, “Models for Predicting Bus Delays,” *Transportation Research Record*, vol. 1623, no. 1, pp. 8–15, Jan. 1998, doi: 10.3141/1623-02.

[22] A. Lajunen, “Lifecycle costs and charging requirements of electric buses with different charging methods,” *Journal of Cleaner Production*, vol. 172, pp. 56–67, Jan. 2018, doi: 10.1016/j.jclepro.2017.10.066.

[23] Liu Tong, “Research on the operation optimization of electric buseswith multiple vehicle types,” Master’s Thesis, Beijing Jiaotong University, BEIJING, China, 2020. Accessed: Mar. 28, 2026. [Online]. Available: https://link.cnki.net/doi/10.26944/d.cnki.gbfju.2020.004040

[24] V. Conti, S. Orchi, M. P. Valentini, M. Nigro, and R. Calò, “Design and evaluation of electric solutions for public transport,” *Transportation Research Procedia*, vol. 27, pp. 117–124, Jan. 2017, doi: 10.1016/j.trpro.2017.12.033.

[25] L. Li, H. K. Lo, F. Xiao, and X. Cen, “Mixed bus fleet management strategy for minimizing overall and emissions external costs,” *Transportation Research Part D: Transport and Environment*, vol. 60, pp. 104–118, May 2018, doi: 10.1016/j.trd.2016.10.001.

[26] Zhou Bin, “Electric Bus Dispatching Based on Improved Genetic Algorithm,” Master’s Thesis, Changsha University of Science & Technology, HUNAN, China, 2012. Accessed: Mar. 28, 2026. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD2012&filename=1012348525.nh

[27] K. An, “Battery electric bus infrastructure planning under demand uncertainty,” *Transport Res C-emer*, vol. 111, pp. 572–587, Feb. 2020, doi: 10.1016/j.trc.2020.01.009.

[28] Z. Gao *et al.*, “Battery capacity and recharging needs for electric buses in city transit service,” *Energy*, vol. 122, pp. 588–600, Mar. 2017, doi: 10.1016/j.energy.2017.01.101.

[29] F. Fei, W. Sun, R. Iacobucci, and J.-D. Schmöcker, “Exploring the profitability of using electric bus fleets for transport and power grid services,” *Transport Res C-emer*, vol. 149, p. 104060, Apr. 2023, doi: 10.1016/j.trc.2023.104060.

[30] B. O. Varga, F. Mariasiu, C. D. Miclea, I. Szabo, A. A. Sirca, and V. Nicolae, “Direct and Indirect Environmental Aspects of an Electric Bus Fleet Under Service,” *Energies*, vol. 13, no. 2, p. 336, Jan. 2020, doi: 10.3390/en13020336.

[31] F. C. Barbosa, "Battery Electric Bus Technology Review - Current Status and Perspectives," SAE Technical Paper, 2022-36–0042, Feb. 2023. doi: 10.4271/2022-36-0042.

[32] S. Borén, "Electric buses' sustainability effects, noise, energy use, and costs," *Int. J. Sustain. Transp.*, vol. 14, no. 12, pp. 956–971, Oct. 2020, doi: 10.1080/15568318.2019.1666324.

[33] R. Kawamoto *et al.*, "Estimation of CO2 Emissions of Internal Combustion Engine Vehicle and Battery Electric Vehicle Using LCA," *Sustainability-basel*, vol. 11, no. 9, Art. no. 9, Jan. 2019, doi: 10.3390/su11092690.

[34] S. Lockrey, K. Verghese, S. Langley, and L. Brennan, "Coke and the environment," in *Decoding Coca-Cola*, Routledge, 2020.

[35] L. Canals Casals, E. Martinez-Laserna, B. Amante García, and N. Nieto, "Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction," *J Clean Prod*, vol. 127, pp. 425–437, Jul. 2016, doi: 10.1016/j.jclepro.2016.03.120.

[36] P. Girardi, A. Gargiulo, and P. C. Brambilla, "A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study," *Int J Life Cycle Assess*, vol. 20, no. 8, pp. 1127–1142, Aug. 2015, doi: 10.1007/s11367-015-0903-x.

[37] M. Hernandez, M. Messagie, M. De Gennaro, and J. Van Mierlo, "Resource depletion in an electric vehicle powertrain using different LCA impact methods," *Resour Conserv Recy*, vol. 120, pp. 119–130, May 2017, doi: 10.1016/j.resconrec.2016.11.005.

[38] M. Gallet, T. Massier, and T. Hamacher, "Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks," *Appl Energ*, vol. 230, pp. 344–356, Nov. 2018, doi: 10.1016/j.apenergy.2018.08.086.

[39] H. Abdelaty, A. Al-Obaidi, M. Mohamed, and H. E. Z. Farag, "Machine learning prediction models for battery-electric bus energy consumption in transit," *Transport Res D-tr E*, vol. 96, p. 102868, Jul. 2021, doi: 10.1016/j.trd.2021.102868.

[40] Y. Chen, Y. Zhang, and R. Sun, "Data-driven estimation of energy consumption for electric bus under real-world driving conditions," *Transport Res D-tr E*, vol. 98, p. 102969, Sep. 2021, doi: 10.1016/j.trd.2021.102969.

[41] P. Li, Y. Zhang, Y. Zhang, Y. Zhang, and K. Zhang, "Prediction of electric bus energy consumption with stochastic speed profile generation modelling and data driven method based on real-world big data," *Appl Energ*, vol. 298, p. 117204, Sep. 2021, doi: 10.1016/j.apenergy.2021.117204.

[42] G. Wang, X. Xie, F. Zhang, Y. Liu, and D. Zhang, "bCharge: Data-Driven Real-Time Charging Scheduling for Large-Scale Electric Bus Fleets," in *2018 IEEE Real-Time Systems Symposium (RTSS)*, Dec. 2018, pp. 45–55. doi: 10.1109/RTSS.2018.00015.

[43] Z. Dabčević, B. Škugor, I. Cvok, and J. Deur, "A Trip-Based Data-Driven Model for Predicting Battery Energy Consumption of Electric City Buses," *Energies*, vol. 17, no. 4, p. 911, Jan. 2024, doi: 10.3390/en17040911.

[44] H. Lin and C. Tang, "Intelligent Bus Operation Optimization by Integrating Cases and Data Driven Based on Business Chain and Enhanced Quantum Genetic Algorithm," *Ieee T Intell Transp*, vol. 23, no. 7, pp. 9869–9882, Jul. 2022, doi: 10.1109/TITS.2021.3121289.

[45] R. M. Sennefelder, R. Martín-Clemente, R. González-Carvajal, and D. Trifonov, "Data Driven Energy Economy Prediction for Electric City Buses Using Machine Learning," *Ieee Access*, vol. 11, pp. 97057–97071, 2023, doi: 10.1109/ACCESS.2023.3311895.

[46] H. Tian, S. E. Li, X. Wang, Y. Huang, and G. Tian, "Data-driven hierarchical control for online energy management of plug-in hybrid electric city bus," *Energy*, vol. 142, pp. 55–67, Jan. 2018, doi: 10.1016/j.energy.2017.09.061.