

Article

Modeling Energy Consumption in Urban Electric Transport: An Adapted Approach Incorporating Operational Factors

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Abstract

The article addresses the problem of estimating the specific electric energy consumption of urban electric transport under real operating conditions. It is substantiated that standardized driving cycles and rated energy consumption values do not always accurately reflect the actual operating modes of vehicles on urban routes, since energy consumption is affected by speed conditions, road conditions, passenger load, ambient temperature, auxiliary systems operation, and the number of stops, accelerations, and braking events. A simplified engineering model is proposed for adjusting the baseline specific electric energy consumption by means of a system of correction factors, which makes it possible to adapt the calculation to specific operating conditions under limited availability of telematics data. A distinctive feature of the proposed approach is the possibility of using a baseline energy consumption value determined from a driving cycle or vehicle specification data, followed by its adjustment according to the characteristics of an actual route. The proposed methodology was experimentally verified using certified trolleybus test data representing a vehicle with characteristics similar to a 12 m urban battery electric bus; however, further validation using dedicated battery electric bus datasets is required. For the reference vehicle operating on route No. 15 in Lutsk, with a route length of 10.2 km, the calculated electric energy consumption was 17.853 kWh at full mass and 12.498 kWh at curb mass, corresponding to approximately 1.75 and 1.23 kWh/km, respectively. The results were compared with experimental data and recent literature sources. The proposed methodology is intended for preliminary engineering assessment of electric energy consumption when detailed operational data are unavailable.

Keywords: urban electric transport; electric bus; trolleybus; energy consumption; specific electric energy consumption; driving cycle; correction factors; real operating conditions



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1. Introduction

Fuel and/or electric energy consumption has always been one of the key issues in vehicle operation. It is well known that, under real operating conditions, consumption differs from the values declared by manufacturers. On the one hand, the technical specifications provided by manufacturers make it possible to compare vehicles; on the other hand, in real operation, numerous factors have either a direct or indirect effect on these indicators [1–4]. Public passenger transport is one of the priority areas, as society is moving towards reducing harmful emissions and traffic congestion while gradually achieving sustainable development goals [5–7]. The first standardized driving cycles appeared in the late 1960s and early 1970s, when the governments of the United States and European countries began to introduce

emission measurements under controlled laboratory conditions. Later, standardized driving cycles were also used to assess vehicle fuel economy and electric energy consumption [8]. The rapid development of modern road transport, the increasing number of vehicles on urban streets, the introduction of special traffic regimes, and other factors lead to a situation in which fuel or electric energy consumption estimated using a standardized driving cycle does not correspond to consumption under real operating conditions. This creates significant challenges for route planning, transport service organization, and rolling stock selection.

The aim of this study is to develop and substantiate a simplified engineering methodology for preliminary estimation of urban electric transport energy consumption under limited availability of telematics data and to assess its adequacy based on control tests conducted on vehicles of different masses.

The scientific contribution of this study lies in the development of an integrated engineering framework for preliminary estimation of urban electric transport energy consumption under limited availability of telematics data. Unlike existing approaches that often require detailed operational datasets, the proposed methodology combines a baseline specific energy consumption value, obtained from standardized driving cycles or vehicle specification data, with a transparent system of operational correction factors synthesized from recent experimental and empirical studies. Rather than introducing new empirical correction factors, the proposed approach integrates the influence of the principal operational conditions into a unified calculation procedure suitable for practical engineering applications. The adequacy of the methodology was assessed using control test results obtained for urban electric transport vehicles of different masses, while further validation of the operational correction factors is identified as an important direction for future research.

Although advanced machine-learning and telematics-based prediction models generally provide higher predictive accuracy, their practical application requires extensive operational datasets, continuous data acquisition, and considerable computational resources. Such information is often unavailable during the preliminary planning of electric bus deployment, route design, fleet modernization, or feasibility studies. Therefore, there remains a practical need for a transparent engineering methodology that enables rapid preliminary estimation of electric energy consumption using only a limited number of readily available operational parameters. The proposed methodology is intended to complement, rather than replace, advanced data-driven prediction approaches.

2. Literature Review

An analysis of recent studies on determining the electric energy consumption of buses indicates considerable scientific interest in this issue. In [9], the authors developed and compared different methods for measuring hydrogen consumption in a bus without the use of specialized measuring equipment and assessed the effect of heating, ventilation, and air conditioning systems on bus fuel consumption. A significant number of studies have focused on evaluating the energy consumption and driving range of electric buses under real driving conditions [10–12]. In [13–15], the authors focused on assessing the energy efficiency of electric buses.

Considering recent advances, researchers are actively implementing machine learning systems to predict electric energy consumption [16–21].

In [22], the authors investigated the prediction of electric energy consumption by buses with electric drives, testing various models with different levels of complexity based on real operating data. As a result, prediction models for the electric energy consumption of electric buses were developed as a basis for their further analysis and structuring.

Thus, the analysis of recent studies makes it possible to identify four key research areas that form the scientific basis for assessing bus energy consumption (Table 1). The first

area is associated with the use of standardized driving cycles, which ensure comparability of results but have limited representativeness with respect to real driving conditions.

Table 1. Key areas for assessing bus energy consumption.

Research Area	Content Focus	Main Issues Considered	Justification
Standardized driving cycles	Use of driving cycles as a tool for laboratory assessment of fuel economy, energy consumption, and emissions	Application of cycles under controlled laboratory conditions; possibility of comparing vehicles using a unified methodology; use of cycles to assess fuel consumption, electric energy consumption, and environmental indicators	Standardized cycles are an important tool for the comparative assessment of vehicles; however, they do not fully reflect the real driving modes of buses in urban environments. As a result, laboratory test results may differ significantly from actual energy consumption during operation.
Real operating conditions of buses	Identification of the factors that determine the actual fuel or electric energy consumption of buses	Influence of speed conditions, number of stops, acceleration and braking events, passenger load, road gradient, traffic congestion, climatic conditions, ambient temperature, operation of heating, ventilation, and air conditioning systems, vehicle technical condition, and driving style	The actual energy consumption of a bus is shaped by a complex set of interrelated operational factors. Therefore, to correctly assess energy consumption, it is necessary to consider not only vehicle parameters but also route conditions, traffic flow, passenger flow, and the operation of auxiliary systems.
Energy consumption prediction models	Development of calculation-based, statistical, or combined models for assessing energy consumption and driving range	Use of real operating data; development of models for predicting electric energy consumption; assessment of electric bus driving range; consideration of route parameters, speed, load, temperature, and driving modes; comparison of models with different levels of complexity	Prediction models make it possible to move from fixed normative values to a more flexible assessment of energy consumption adapted to specific operating conditions. However, the accuracy of such models depends on the completeness of input data, the correct selection of parameters, and the ability to account for variable driving conditions.
Application of machine learning	Use of digital methods for analyzing large datasets to improve prediction accuracy	Application of machine learning algorithms, deep learning, multi-model prediction, and real-time models; analysis of large telematics and route datasets; prediction of instantaneous power demand or trip-based energy consumption; integration of data on speed, passenger flow, route characteristics, road conditions, and auxiliary loads	Machine learning methods are among the most promising approaches for predicting bus energy consumption, as they make it possible to identify complex nonlinear relationships between driving conditions and energy consumption. At the same time, their application requires high-quality data, model validation, and explainability of the obtained results.

The second area covers the study of actual bus operating conditions and the factors affecting energy consumption. The third area concerns the development of models for predicting energy consumption and driving range, while the fourth involves the application

of machine learning methods to improve the accuracy of such predictions. The combination of these areas substantiates the need to adapt driving cycles to the real operating conditions of urban public transport.

These four areas are interconnected as successive levels of research into bus energy consumption: from normative laboratory assessment to the analysis of real driving conditions, then to the development of predictive models, and, at the final stage, to intelligent prediction based on large datasets.

Standardized driving cycles form the initial methodological basis for assessing bus energy consumption; however, their limited correspondence to real driving conditions necessitates the consideration of operational factors. These factors, in turn, provide the basis for developing energy consumption prediction models, while the application of machine learning methods makes it possible to improve the accuracy of such models through the analysis of large volumes of actual operating data. Thus, the identified areas are not isolated but form a unified logical research framework, extending from a standardized test cycle to adapted energy consumption prediction under real operating conditions.

Despite the considerable progress achieved in physics-based, statistical, and machine-learning approaches, most existing methods require detailed telematics, vehicle CAN-bus data, or long-term operational measurements. In practical engineering applications, particularly during preliminary route planning, fleet assessment, or charging infrastructure design, such datasets are often unavailable. Therefore, there remains a need for a transparent engineering methodology capable of integrating the influence of the principal operational factors into a single calculation framework using limited input information. The proposed approach aims to address this gap. The relationships among these research directions and the position of the proposed engineering methodology within the overall evolution of energy consumption assessment approaches are illustrated in Figure 1.

Figure 1 presents the general evolution of approaches to urban electric transport energy consumption assessment. Machine learning and forecasting methods are included only to demonstrate the broader scientific context and possible future development of energy consumption prediction techniques. The present study focuses exclusively on a simplified engineering methodology intended for preliminary energy consumption assessment under limited telematics availability.

Compared with conventional approaches based solely on standardized driving cycles or manufacturer specification data, the proposed methodology provides a practical engineering tool for adapting baseline energy consumption to representative operating conditions using transparent correction factors.

A similar discrepancy between standardized testing conditions and real-world operation has also been reported for fuel cell buses and other fuel cell electric vehicles. Recent studies have demonstrated that actual energy consumption and energy management performance are strongly influenced by dynamic passenger loading, thermal loads, traffic conditions, and operating environments, which cannot be fully represented by standardized driving cycles alone [23,24].

These findings indicate that the challenge of adapting standardized energy consumption estimates to realistic operating conditions is common across different zero-emission public transport technologies, further supporting the need for practical engineering methodologies applicable when detailed operational datasets are unavailable.

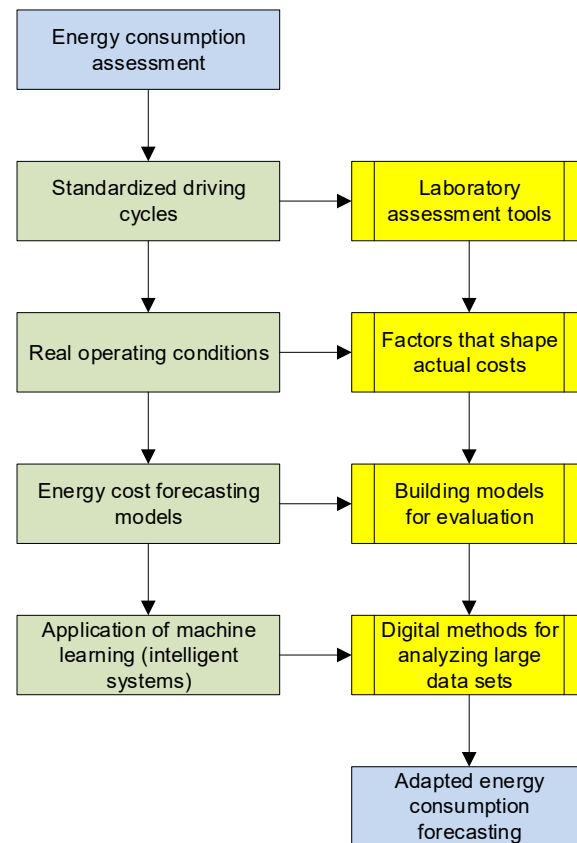


Figure 1. Conceptual framework for the development of energy consumption assessment methods.

3. Methods

3.1. General Structure of the Model

In scientific literature, the prediction of electric bus energy consumption is considered a multifactorial task, in which a baseline or normative value of specific energy consumption is adjusted regarding real operating conditions. In particular, standardized SORT/E-SORT cycles are used to obtain comparable values of bus energy consumption under reproducible conditions. International Association of Public Transport (UITP) states that E-SORT is intended for the accurate and reproducible determination of the traction energy consumption of electric buses and the assessment of their driving range, which confirms the feasibility of using a standardized value as a baseline for further adjustment.

In the proposed methodology, the baseline specific electric energy consumption (E_0) represents the reference energy demand of a vehicle operating under standardized conditions. This value may be obtained either from standardized driving cycles (e.g., SORT/E-SORT), manufacturer specification data, or experimentally determined reference operating modes. The baseline value serves as the starting point for subsequent adaptation to actual operating conditions through a system of correction factors. Such an approach makes it possible to preserve the comparability provided by standardized testing while accounting for the influence of operational factors encountered during real urban service. The procedure used to determine the baseline specific electric energy consumption adopted in this study is described in Section 3.2.

Similar logic can be observed in studies where electric bus energy consumption is assessed through a combination of physical, empirical, and statistical models. Li et al. proposed a hybrid physics-based and data-driven model in which the baseline energy consumption of an electric bus is determined using a simplified physical model, while the influence of additional factors is refined using machine learning algorithms [25]. The

model considers rolling resistance, braking energy consumption, air conditioning, and other factors.

In [26], it is shown that external factors, real operating data, route topography, vehicle parameters, and driving conditions are important when assessing the energy consumption of battery electric buses. This confirms the methodological feasibility of using a multifactorial system of correction factors, which allows the specification-based value to be adapted to the conditions of a particular route.

The importance of considering passenger load is confirmed by the study in [27], which shows that an increase in vehicle mass due to changes in the number of passengers increases bus energy consumption.

Real route conditions also have a significant effect on energy consumption. In [28], the authors proposed an electric bus energy consumption model based on real-world data from a large public transport network in Singapore. The authors emphasize that energy demand should be analyzed separately for each bus line, since even routes of similar length may differ significantly in energy consumption due to driving profile, number of stops, speed, passenger flow, and auxiliary loads.

Recent studies also emphasize the influence of temperature, auxiliary systems, and driving modes. Based on experimental data from a 12 m electric bus, a group of researchers analyzed the effects of passenger number, route characteristics, driving conditions, temperature, and auxiliary systems operation on energy consumption [29]. The authors established relationships between total distance, trip duration, average speed, driving style, route characteristics, external and internal temperature, and the energy consumed by traction motors and the climate control system.

Based on the conducted analysis, a simplified multifactorial empirical model is proposed, which can be used to predict the electric energy consumption of buses. This model is based on standardized or specification-based energy consumption values, which are used as baseline values, while real operating conditions are accounted for through a system of coefficients:

$$E_l = E_0 \cdot L \cdot K_v \cdot K_r \cdot K_p \cdot K_t \cdot K_{aux} \cdot K_{stop} \quad (1)$$

where

E_l —total electric energy consumption on the route, kWh;

E_0 —baseline specific electric energy consumption, kWh/km;

L —route length or mileage, km;

K_v —coefficient accounting for speed conditions;

K_r —coefficient accounting for road conditions and route profile;

K_p —coefficient accounting for passenger compartment occupancy;

K_t —coefficient accounting for temperature conditions;

K_{aux} —coefficient accounting for the operation of auxiliary systems, including heating, ventilation, air conditioning, lighting, and compressor equipment;

K_{stop} —the coefficient accounting for stops, accelerations, and braking events.

The multiplicative structure adopted in Equation (1) represents a simplified engineering approximation that assumes each correction factor modifies the baseline specific energy consumption proportionally to its individual influence. This approach is widely used in engineering calculations because it preserves the physical interpretation of each factor, facilitates practical application, and enables independent adjustment of the baseline value using readily available operational information. Although interactions between operational factors may occur in real driving conditions, the multiplicative formulation provides a transparent and computationally efficient framework for preliminary engineering assessment when comprehensive multivariable datasets are unavailable.

The coefficient accounting for speed conditions is used to consider the travel speed of an electric bus. An analysis of recent literature sources shows that the specific energy consumption of an electric bus has a nonlinear relationship with average speed. In the range of low urban speeds, an increase in average speed is accompanied by a decrease in specific electric energy consumption, which can be explained by the reduced share of acceleration, braking, and idling modes. For an urban electric bus in the 15–18 t mass category, the minimum energy consumption values are reasonably expected within the speed range of 35–45 km/h. With a further increase in speed, specific energy consumption gradually increases due to the increase in motion resistance, primarily aerodynamic drag [29–31]. Based on the results of the studies presented in [32], the coefficient (K_v) was determined, as shown in Table 2.

Table 2. Values of the coefficient accounting for speed conditions (based on [32]).

Average Speed, km/h	Approximate Specific Energy Consumption, kWh/km	Coefficient Relative to the Level at 50 km/h
10	2.70	2.11
20	1.75	1.37
30	1.35	1.05
40	1.20	0.94
50	1.28	1.00
60	1.42	1.11

A speed of 50 km/h was adopted as the baseline for determining the speed condition coefficient, since it corresponds to the typical upper limit of permissible vehicle speed in urban conditions and can be considered a normative reference for a steady route section without significant influence of traffic congestion. Normalizing energy consumption to a speed of 50 km/h makes it possible to assess the extent to which actual urban driving modes with lower average speeds—10, 20, 30, or 40 km/h—increase or decrease specific electric energy consumption compared with conditionally free-flow urban traffic.

The coefficient accounting for road conditions and route profile, (K_r), should be used to account for the influence of longitudinal road gradient, road surface condition, and route profile complexity on electric bus energy consumption. A typical urban route with satisfactory pavement conditions and minor gradients is adopted as the baseline condition, for which ($K_r = 1.00$). For routes with moderate gradients and individual sections of a more complex profile, the coefficient may range from 1.05 to 1.15, while for routes with complex terrain, significant elevation differences, or deteriorated road surface conditions, it may range from 1.15 to 1.30 or higher [29,33,34]. Based on the above-mentioned literature sources, the recommended values of the coefficient accounting for road conditions and route profile, (K_r), are presented in Table 3.

For practical application of the proposed methodology, route categories are defined according to the average longitudinal gradient of the route and the general pavement condition. The indicated gradient ranges should be regarded as engineering guidelines rather than strict classification limits, since actual energy consumption also depends on the length and distribution of ascending and descending sections, traffic conditions, and vehicle operating characteristics.

Since the baseline specific electric energy consumption of an electric bus is usually determined for a vehicle at full mass, the passenger compartment occupancy coefficient, (K_p), should be normalized relative to the full mass of the bus. In this case, the baseline operating mode is assumed to correspond to the full calculated passenger occupancy, for which ($K_p = 1.00$). With a lower number of passengers, the actual mass of the bus decreases; therefore, the coefficient (K_p) takes values below unity (Table 4).

Table 3. Values of the coefficient accounting for road conditions and route profile (K_r) based on [29,33,34].

Route Type	Longitudinal Gradient/Pavement Condition	Recommended Value, K_r
Flat route with good pavement condition	Average longitudinal gradient < 2%; paved road in good condition	0.95–1.00
Typical urban route	Average gradient 2–4%; asphalt pavement in satisfactory condition	1.00
Route with moderate gradients	Average gradient 4–6%; several sections with grades up to 8%; satisfactory pavement	1.05–1.15
Route with complex terrain	Average gradient 6–8%; frequent grades above 8%; mountainous or hilly urban routes	1.15–1.30
Difficult road conditions	Average gradient > 8%; deteriorated pavement with increased rolling resistance	1.30–1.50

Table 4. Values of the passenger compartment occupancy coefficient, (K_p), based on [22,29,33,34].

Passenger Compartment Occupancy	Operating Mode Description	Approximate Coefficient, K_p
0%	Empty bus, curb mass only	0.65–0.70
25%	Low passenger load	0.70–0.75
50%	Medium passenger load	0.75–0.85
75%	High passenger load	0.85–0.95
100%	Full calculated occupancy, full bus mass	1.00

The coefficient accounting for temperature conditions, (K_t), is intended to adjust the baseline specific electric energy consumption of an electric bus depending on ambient temperature. Temperature affects energy consumption through changes in battery efficiency, the need for cabin heating or air conditioning, the operation of battery thermal management systems, and increased auxiliary energy loads. The temperature range of +15 to +25 °C is adopted as the baseline condition, for which ($K_t = 1.00$). At low temperatures, the coefficient may increase to 1.35–1.60, and under severe frost conditions, to 1.60–1.90. At high temperatures, when cabin air conditioning and battery cooling are actively operating, the coefficient should be taken within the range of 1.05–1.40, depending on the intensity of the thermal load (Table 5).

The coefficient accounting for auxiliary systems operation, (K_{aux}), is intended to adjust the baseline specific electric energy consumption of an electric bus depending on the operating mode of non-traction electrical consumers. Such consumers include interior and exterior lighting systems, pneumatic system compressor equipment, door drives, windshield wipers, information displays, validators, video surveillance systems, communication systems, and other low-voltage network components. The typical operation of auxiliary systems is adopted as the baseline mode, for which ($K_{aux} = 1.00$). Under increased auxiliary load, the coefficient may range from 1.03 to 1.08, while under difficult operating conditions it may range from 1.08 to 1.15. For very difficult conditions associated with prolonged stops, frequent door-opening cycles, intensive operation of compressor equipment, windshield wipers, and lighting, the coefficient may be increased to 1.15–1.25. At the same time, the operation of heating, ventilation, and air conditioning systems should be accounted for separately through the temperature condition coefficient (K_t) to avoid double counting of HVAC energy consumption [29,33,36].

The coefficient accounting for stops, accelerations, and braking events, (K_{stop}), should be determined with consideration of regenerative braking, since during electric bus deceleration part of the kinetic energy can be returned to the battery. In this case, the effect of stops on energy consumption is determined not only by the number of acceleration–braking cycles but also by recuperation efficiency. The additional energy losses per cycle can be

represented as the difference between the energy consumed during acceleration and the energy recovered during braking. Since recuperation is not complete and depends on battery state, temperature, speed, braking intensity, and control algorithms, an increase in the number of stops still leads to higher specific electric energy consumption. A stop density of 1–2 stops per km of route should be adopted as the baseline condition, for which ($K_{stop} = 1.00$). At higher stop densities, the coefficient increases; however, its values should be adjusted with consideration of partial energy recovery through regenerative braking (Table 6) [29,34,37].

Table 5. Values of the coefficient accounting for temperature conditions, (K_t), based on [29,35].

Ambient Temperature	Condition Description	Approximate Coefficient, K_t
below $-15\text{ }^{\circ}\text{C}$	Very cold conditions, intensive cabin heating and battery heating	1.60–1.90
$-15\ldots-5\text{ }^{\circ}\text{C}$	Cold conditions, significant load on heating systems	1.35–1.60
$-5\ldots+5\text{ }^{\circ}\text{C}$	Transitional cold period, moderate heating	1.15–1.35
$+5\ldots+15\text{ }^{\circ}\text{C}$	Moderately cool conditions, minor additional load	1.05–1.15
$+15\ldots+25\text{ }^{\circ}\text{C}$	Baseline comfortable conditions, minimal HVAC demand	1.00
$+25\ldots+30\text{ }^{\circ}\text{C}$	Warm conditions, moderate air conditioning operation	1.05–1.15
$+30\ldots+35\text{ }^{\circ}\text{C}$	Hot conditions, more intensive air conditioning	1.15–1.30
above $+35\text{ }^{\circ}\text{C}$	Very hot conditions, significant load from air conditioning and battery cooling	1.25–1.40

Table 6. Values of the coefficient accounting for stops, accelerations, and braking events (K_{stop}) based on [29,34,37].

Stop Density	Typical Operating Conditions	Recommended Value of (K_{stop}) Accounting for Regenerative Braking
Up to 1 stop/km	Urban or suburban routes with long distances between stops, coordinated traffic flow, low traffic congestion	0.95–1.00
1–2 stops/km	Typical urban routes with moderate passenger demand and normal traffic conditions (baseline)	1.00
2–3 stops/km	Dense urban routes with regular passenger boarding/alighting, frequent acceleration–braking cycles, moderate traffic congestion	1.03–1.10
3–4 stops/km	Central urban areas with high passenger demand, signalized intersections, and frequent stop-and-go operation	1.08–1.18
More than 4 stops/km	Highly congested city centres with intensive passenger exchange, short spacing between stops, and repeated acceleration–braking cycles	1.15–1.30

The proposed stop coefficient represents an aggregated engineering correction that accounts for the overall influence of stop frequency, acceleration, deceleration, and regen-

erative braking on electric energy consumption. It does not explicitly model the detailed behaviour of regenerative braking, which in practice depends on factors such as braking intensity, vehicle speed, battery state of charge, ambient temperature, and traction control strategy. Consequently, the proposed coefficient should be regarded as a simplified engineering approximation suitable for preliminary energy consumption assessment rather than as a detailed physical model of regenerative energy recovery.

The stop density ranges presented in Table 6 are intended as engineering guidelines for preliminary energy consumption assessment. When more detailed operational data are available, the coefficient may be refined using actual route characteristics, including the number of scheduled stops, signalized intersections, traffic congestion, and average regenerative braking efficiency.

The interaction between K_t and K_{stop} is recognized as a limitation of the simplified engineering approach adopted in this study. Nevertheless, the magnitude of this interaction is considerably smaller than the overall influence of ambient temperature represented by K_t , and therefore the coefficients were treated as independent to preserve the transparency and practical applicability of the proposed methodology.

The system of correction factors reflects the difference between actual operating conditions and standard or average driving modes. This approach makes it possible to combine the simplicity of normative calculation-based assessment with the ability to adapt the results to a specific route, passenger load, traffic situation, climatic conditions, and auxiliary systems operating mode.

The proposed correction coefficients were not derived from a single experimental dataset but synthesized from recent experimental and empirical studies covering different electric buses, trolleybuses, operating routes, and climatic conditions. Consequently, the recommended coefficient ranges are intended to represent typical engineering conditions rather than vehicle-specific calibration parameters. Their applicability to other vehicle types depends on the similarity of vehicle characteristics and operating conditions and may require further refinement when additional experimental data become available. This synthesis-based approach was intentionally adopted to improve the general engineering applicability of the proposed methodology, although future calibration using harmonized large-scale datasets would further refine the recommended coefficient ranges.

The proposed model describes the energy consumption of an urban electric vehicle at the level of the traction–route energy balance. In this model, baseline specific energy consumption is adjusted according to driving conditions, route profile, passenger load, temperature, auxiliary systems, and the number of stops. Such a structure is applicable to both trolleybuses and battery electric buses, since the main components of mechanical work at the wheels are determined by the same physical factors. The differences between the overhead contact power supply of a trolleybus and the battery power supply of an electric bus are accounted for at the level of baseline specific energy consumption and correction factors, primarily the temperature coefficient, the auxiliary systems coefficient, and the recuperation coefficient.

3.2. Calculation of Electric Energy Consumption

To verify the adequacy of the proposed model, the calculation of electric energy consumption was performed using Equation (1) for route No. 15 in Lutsk. The adopted coefficient values are presented in Table 7.

Table 7. Adopted indicator values for calculating electric energy consumption.

Indicator	Symbol	Adopted Value for the T70110 Trolleybus	
		Full Mass	Curb Mass
Baseline specific electric energy consumption, kWh/km	E_0	1.183	1.183
Route length, km	L	10.2	10.2
Coefficient accounting for speed conditions	K_v	1.37	1.37
Coefficient accounting for road conditions and route profile	K_r	1.00	1.00
Coefficient accounting for passenger compartment occupancy	K_p	1.00	0.70
Coefficient accounting for temperature conditions	K_t	1.00	1.00
Coefficient accounting for auxiliary systems operation	K_{aux}	1.00	1.00
Coefficient accounting for stops, accelerations, and braking events	K_{stop}	1.08	1.08

The exact coefficient values adopted for the case study were selected on the basis of the documented operating conditions of route No. 15 and the reference conditions defined in Tables 2–6. The average operating speed on the route was approximately 20 km/h, corresponding to $K_v = 1.37$. The route was considered a typical urban route with satisfactory pavement conditions and no pronounced longitudinal gradients; therefore, $K_r = 1.00$ was adopted. For the full-mass case, the vehicle was assumed to operate at full calculated passenger occupancy, corresponding to $K_p = 1.00$, whereas for the curb-mass case the absence of passengers was represented by $K_p = 0.70$. The tests were conducted under baseline temperature conditions without intensive heating or air-conditioning demand, and with normal auxiliary-system operation; therefore, $K_t = 1.00$ and $K_{aux} = 1.00$ were used. The stop density and acceleration–braking frequency corresponded to a typical urban route with frequent stops, for which $K_{stop} = 1.08$ was selected. All adopted parameters are summarized in Table 7.

The adopted coefficient values represent the documented operating conditions of the reference route and are intended to illustrate a typical urban operating scenario rather than universally applicable operating conditions.

The T70110 trolleybus (Automobile Company “Bogdan Motors” PJSC, Lutsk, Ukraine) was used as the reference object for model verification since, in terms of full mass, passenger capacity, operating mode on an urban route, and traction electric drive structure, it is representative of 12 m urban electric buses in the 15–20 t mass category. The availability of experimental control test data makes it possible to use this vehicle to validate the main part of the proposed methodology, which accounts for the influence of vehicle mass, speed, route characteristics, and driving conditions on electric energy consumption. Accordingly, the trolleybus was used as a surrogate validation platform for the proposed engineering methodology rather than as evidence of complete equivalence with battery electric buses.

For the verification presented in this study, the baseline-specific electric energy consumption of 1.183 kWh/km was determined using the calculation methodology reported in [38] and the elementary driving cycle shown in Figure 2.

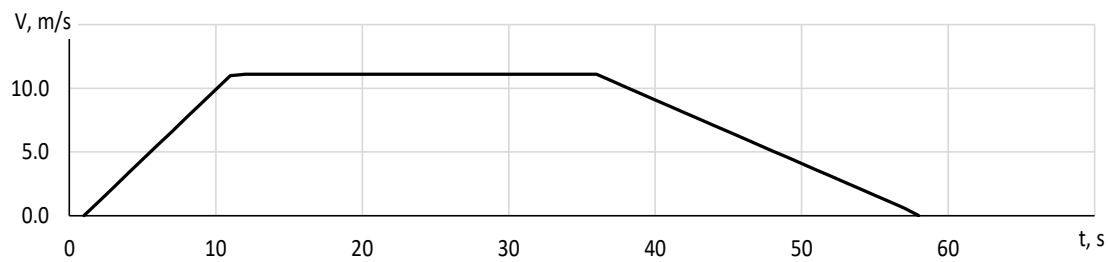


Figure 2. Elementary driving cycle.

The adopted driving cycle reproduces the characteristic operating phases of urban public transport, including acceleration, cruising, deceleration, and stopping. The driving cycle used in this paper comprises only acceleration, constant speed, and deceleration phases. Their durations and speed variations are relatively simple and do not fully reflect the characteristics of actual operation. Therefore, the adopted elementary driving cycle serves only as a standardized reference for determining the baseline specific electric energy consumption, while the influence of real operating conditions is subsequently incorporated through the proposed correction coefficients. Vehicle technical characteristics, traction drive parameters, and resistance forces were incorporated into the calculation procedure to obtain a reference energy consumption value under standardized operating conditions, which subsequently served as the baseline input for the proposed correction-factor methodology.

The technical characteristics of the reference trolleybus are presented in Table 8. The choice of this vehicle was determined by the availability of experimental test results obtained by the Urban Electric Transport Testing Center of the State Enterprise “Research and Design-Technological Institute of Municipal Economy”, accredited in accordance with ISO/IEC 17025 [39].

Table 8. Technical characteristics of the T70110 trolleybus.

Index Name	Trolleybus Modification
	T70110
Overall length by the body elements, mm	11,960
Overall width, mm	2550
Overall height, mm	3800
Wheel base, mm	5860
Track of front/rear axis, mm	2160/1890
Passenger capacity, persons	105
Empty mass, kg	11,800
Technically admissible maximum mass, kg	18,940
Gear ratio of a main gear	9.82
Wheel tires	275/70R 22.5
Tire pressure, kgs/cm ²	8.0
Traction engine	ЕД-139АУ2
Impulse converter (IGBT)	Cegelec CDC 050P
Static converter 600/27 V, 3ph 400 V	Cegelec SMTK 7.0Z
Auxiliary brake system	Electrodynamic braking as a function of tractive electric engine

According to the calculation results, the cumulative electric energy consumption during the elementary driving cycle is 1.85 MJ, or 0.514 kWh (Figure 3), while the corresponding instantaneous traction power profile is presented in Figure 4.

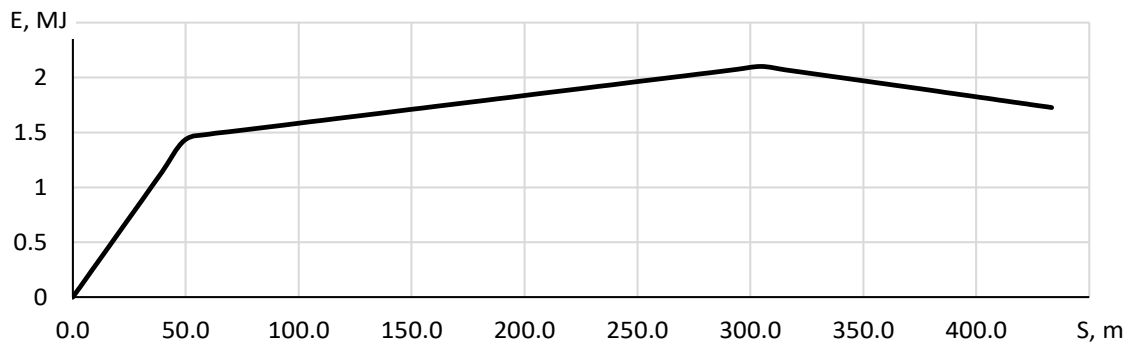


Figure 3. Cumulative electric energy consumption during the elementary driving cycle.

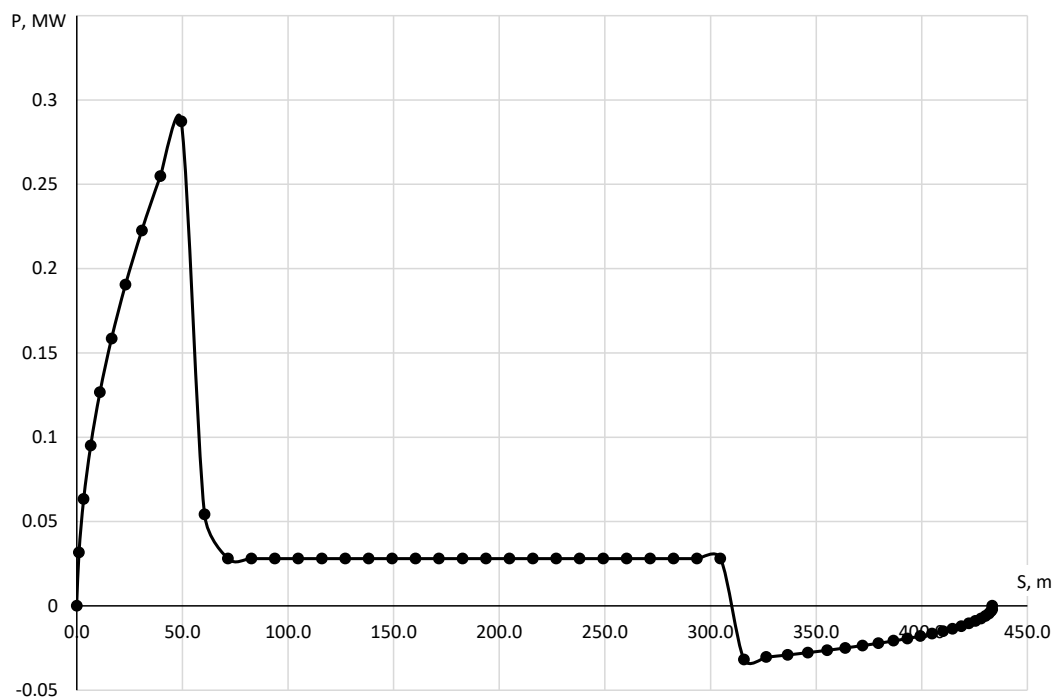


Figure 4. Instantaneous electric power during the elementary driving cycle.

The resulting specific electric energy consumption of the trolleybus is 1.183 kWh/km.

According to the calculation results, the electric energy consumption on route No. 15, with a length of 10.2 km, was 17.853 kWh at full mass and 12.498 kWh at curb mass, corresponding to approximately 1.75 and 1.23 kWh/km, respectively.

4. Discussion

The calculated values of electric energy consumption were compared with the experimental data obtained during trolleybus testing (Table 9), as reported in test protocol T701.10-3. The tests were conducted by the Urban Electric Transport Testing Center of the State Enterprise “Research and Design-Technological Institute of Municipal Economy”.

The experimental validation was based on certified control tests conducted by the Urban Electric Transport Testing Center. For each loading condition (curb mass and technically permissible maximum mass), three control runs were performed. The results presented in Table 9 correspond to the arithmetic mean of the measured values obtained during these control runs, in accordance with the testing protocol. The tests on the control route were carried out at an ambient temperature of +23 °C under real operating conditions with all scheduled stops.

Table 9. Model adequacy verification.

Indicators to Be Determined	Actual Values of Indicators Obtained During Testing		Calculated Values		Deviation, %	
	Curb Mass	Full Mass	Curb Mass	Full Mass	Curb Mass	Full Mass
Electric energy consumption on the control route, kWh	12.5	19.0	12.497	17.853	−0.02	−6.03
Specific electric energy consumption on the control route, Wh/(t·km)	103.9	98.3	103.835	92.416	−0.06	−5.98

Apart from the vehicle loading condition (curb mass and technically permissible maximum mass), all principal operating conditions remained unchanged during the validation procedure, including the test route, ambient temperature, driving conditions, and the adopted test methodology. Consequently, the observed differences between the calculated and measured energy consumption values primarily reflect the influence of vehicle mass.

Since only the averaged certified test results were available from the testing protocol, statistical indicators such as standard deviation or confidence intervals could not be determined within the scope of the present study. Similar calculations were performed for the T60112, T90110 (Automobile Company “Bogdan Motors” PJSC, Lutsk, Ukraine), and E301A2 trolleybuses (Lviv Bus Plant (LAZ), Lviv, Ukraine). The calculation results are presented in Table 10.

Table 10. Results of the adequacy verification of the proposed model for vehicles of different models.

Indicators to Be Determined	Actual Values of Indicators Obtained During Testing		Calculated Values		Deviation, %	
	Curb Mass	Full Mass	Curb Mass	Full Mass	Curb Mass	Full Mass
T60112						
Electric energy consumption on the control route, kWh	13.05	19.4	11.8	16.856	−9.58	−13.11
Specific electric energy consumption on the control route, Wh/(t·km)	118.0	106.5	106.46	92.48	−9.78	−13.16
T90110						
Electric energy consumption on the control route, kWh	16.5	26.5	18.06	25.81	+9.45	−2.60
Specific electric energy consumption on the control route, Wh/(t·km)	88.0	81.0	96.27	81.95	+9.40	+1.17
E301A2						
Electric energy consumption on the control route, kWh	19.6	29.4	17.81	25.44	−9.12	−13.45
Specific electric energy consumption on the control route, Wh/(t·km)	110.4	98.0	100.3	84.82	−9.15	−13.45

The verification results indicate a sufficiently high agreement between the calculated and actual values. For the T70110 trolleybus at curb mass, the actual electric energy consumption on the control route was 12.5 kWh, while the calculated value was 12.497 kWh. The deviation was only -0.02% , indicating an almost complete agreement between the results. At full mass, the actual consumption was 19.0 kWh, while the calculated value was 17.853 kWh, corresponding to a deviation of -6.03% . A similar trend was observed for specific electric energy consumption: the deviation was -0.06% at curb mass and -5.98% at full mass. Thus, for the reference vehicle, the model provides acceptable accuracy in calculating both total and specific electric energy consumption.

Additional verification of the model adequacy was performed for other urban electric transport models, namely the T60112, T90110, and E301A2 trolleybuses. This made it possible to assess the applicability of the proposed approach to vehicles with different capacities, masses, and design configurations. A comparison of the actual and calculated values showed that the deviations generally remained within limits acceptable for engineering calculations. For some vehicles, the discrepancy between experimental and calculated data was approximately 9–13%, which may be due to differences in vehicle technical condition, traction electric drive efficiency, driving modes on the control route, auxiliary systems operation, regenerative braking conditions, and the actual nature of loading.

Overall, the verification results show that, under identical route and environmental conditions, the proposed model adequately reflects changes in electric energy consumption associated with different vehicle loading conditions. The smallest deviations were obtained for the T70110 trolleybus, confirming the correctness of the initial assumptions of the model for the reference object of the study. At the same time, the larger deviations observed for some models indicate the need for further refinement of the correction factors, particularly those accounting for speed conditions, route profile, passenger load, auxiliary systems operation, and regenerative braking efficiency.

Thus, the comparison of calculated and experimental data confirms the applicability of the proposed model. The obtained deviations generally do not exceed 10–13%, which is acceptable for preliminary engineering assessment of electric energy consumption by urban electric transport. Accordingly, the proposed methodology should be interpreted as a simplified engineering assessment tool rather than a universal predictive model, particularly in cases where detailed telematics or long-term operational measurements are unavailable. Further improvement in model accuracy can be achieved by refining the correction factors based on an expanded sample of experimental data for different vehicle models and operating conditions.

It should be emphasized that the experimental validation presented in this study was limited to assessing the influence of vehicle mass on electric energy consumption, as reliable control test data under different loading conditions were available for the investigated trolleybus models. The remaining operational correction factors, including those related to speed conditions, route profile, ambient temperature, auxiliary systems operation, and stop density, were not calibrated using dedicated experimental measurements within this study. Instead, their recommended values were established through a synthesis of recent experimental and empirical findings reported in the scientific literature. Therefore, the proposed correction factors should be regarded as engineering recommendations intended for preliminary energy consumption assessment under limited telematics availability. Their further refinement and validation using comprehensive operational datasets collected under controlled variations in individual operating factors constitute an important direction for future research.

The verification results obtained for trolleybuses can be used for the preliminary assessment of battery electric bus energy consumption, provided that the baseline specific

consumption values and correction factors are appropriately refined. This is explained by the fact that, for both types of vehicles, the main energy losses during motion are determined by the same factors: mass, speed, acceleration, road profile, number of stops, and auxiliary systems operation. At the same time, for battery electric buses, additional factors must be considered, including losses in the battery system, energy conversion efficiency, recuperation limitations depending on the state of charge and battery temperature, as well as the energy consumption of the thermal management system [40]. Therefore, in its current form, the proposed model should be regarded as a tool for preliminary engineering assessment rather than a fully universal model for all types of electric buses.

The use of trolleybus test data does not imply complete equivalence between trolleybuses and battery electric buses. Rather, the selected vehicle serves as a representative reference platform because of its comparable mass, passenger capacity, traction electric drive, and urban operating characteristics.

To illustrate the practical application of the proposed engineering methodology, scenario-based calculations were performed for electric buses of different mass categories under representative operating conditions. Since comprehensive experimental datasets covering all investigated operating scenarios are not currently available, the calculated values were compared with representative ranges reported in the recent literature rather than with dedicated experimental measurements. The results are presented in Tables 11 and 12.

Table 11. Illustrative application of the proposed methodology: baseline and moderate operating conditions.

Operating Conditions	Adopted Operating Condition Coefficients	Overall Coefficient	Full Mass of the Electric Bus	Calculated Specific Consumption, kWh/km	Comparison with Literature Data
Baseline/specification-based conditions	No correction	1.00	10–15 t	0.95	The value corresponds to the lower limit of real-world estimates for lighter urban electric buses; in the study by Ergül et al., the actual route-specific values ranged from 0.94 to 1.85 kWh/km [33].
Baseline/specification-based conditions	No correction	1.00	15–20 t	1.18	It is consistent with the baseline value of 1.183 kWh/km adopted in the methodology for a vehicle with a mass of approximately 19 t [22].
Baseline/specification-based conditions	No correction	1.00	over 20 t	1.55	For 18 m/articulated electric buses, Klapproth et al. use an approximate value of 1.6 kWh/km [31].
Typical urban route	Speed at 20 km/h—1.37; stops—1.08; others—1.00	1.48	10–15 t	1.41	The value falls within the range of actual values of 0.94–1.85 kWh/km obtained on real routes [33].
Typical urban route	Speed at 20 km/h—1.37; stops—1.08; others—1.00	1.48	15–20 t	1.75	The value is close to the calculation obtained using the proposed methodology for full mass on route No. 15: 17.853 kWh over 10.2 km, corresponding to approximately 1.75 kWh/km [32].
Typical urban route	Speed at 20 km/h—1.37; stops—1.08; others—1.00	1.48	over 20 t	2.29	For articulated and heavier buses, this value is higher than the average value of 1.6 kWh/km but remains realistic for congested urban traffic [31].

Table 12. Illustrative application of the proposed methodology: severe operating conditions.

Operating Conditions	Adopted Operating Condition Coefficients	Overall Coefficient	Full Mass of the Electric Bus	Calculated Specific Consumption, kWh/km	Comparison with Literature Data
Complicated summer conditions	Speed—1.37; route profile—1.05; temperature +30 to +35 °C—1.20; auxiliary systems—1.08; stops—1.08	2.01	10–15 t	1.91	The value is close to the upper limit of real-world route-specific values; Belloni et al. emphasize the influence of temperature, route characteristics, stops, and auxiliary systems on energy consumption [29].
Complicated summer conditions	Speed—1.37; route profile—1.05; temperature +30 to +35 °C—1.20; auxiliary systems—1.08; stops—1.08	2.01	15–20 t	2.38	The value falls within the range of increased consumption typical of urban electric buses operating under complex temperature and route conditions [29,33].
Complicated summer conditions	Speed—1.37; route profile—1.05; temperature +30 to +35 °C—1.20; auxiliary systems—1.08; stops—1.08	2.01	over 20 t	3.12	The value is consistent with the literature range of 2.0–4.6 kWh/km for different types of electric bus service [36].
Difficult winter conditions	Speed—1.37; route profile—1.15; temperature –15 to –5 °C—1.45; auxiliary systems—1.10; stops—1.08	2.71	10–15 t	2.58	The increase is explained by heating operation, battery thermal management, and reduced efficiency under cold conditions; Klaproth et al. directly analyze the effect of temperature on specific energy consumption (SEC) [31].
Difficult winter conditions	Speed—1.37; route profile—1.15; temperature –15 to –5 °C—1.45; auxiliary systems—1.10; stops—1.08	2.71	15–20 t	3.21	The value is close to the upper levels reported in the literature, where such levels are explained by the combined influence of temperature, load, route profile, and driving conditions; Klaproth et al. report a range of 1.109–3.05 kWh/km under variable conditions [31].
Difficult winter conditions	Speed—1.37; route profile—1.15; temperature –15 to –5 °C—1.45; auxiliary systems—1.10; stops—1.08	2.71	over 20 t	4.21	The value falls within the range of 2.0–4.6 kWh/km reported by Basma et al. for different types of electric bus service and complex operating modes [36].

The comparison presented in Table 11 is therefore intended to assess the consistency of the proposed methodology with published experimental evidence rather than to provide an independent experimental validation of the model.

The calculations show that, under baseline conditions, the specific energy consumption of electric buses is approximately 0.95–1.55 kWh/km. In typical urban traffic with frequent stops, it increases to 1.41–2.29 kWh/km, while under difficult winter conditions it may reach 2.58–4.21 kWh/km. The obtained values are consistent with recent literature data; however, in certain cases, the coefficient values require refinement based on actual telematics or experimental data corresponding to specific operating conditions.

The influence of individual correction factors on the final energy consumption estimate is proportional to their multiplicative contribution in Equation (1). Consequently, factors with the largest deviation from unity (such as vehicle loading, operating speed, ambient temperature, and auxiliary energy demand) exert the greatest influence on the calculated

energy consumption. A comprehensive quantitative sensitivity analysis is beyond the scope of the present study and will be addressed in future work.

The influence of individual correction factors on the final energy consumption estimate is proportional to their multiplicative contribution in Equation (1). In terms of the departure from the baseline scenario, factors with coefficients farthest from unity (such as vehicle loading, operating speed, ambient temperature, and auxiliary energy demand) produce the largest scenario correction. However, owing to the multiplicative structure, equal relative perturbations of individual coefficients are transferred proportionally to E_l . Therefore, with all other inputs held constant, a $\pm 10\%$ change in any one coefficient produces a $\pm 10\%$ change in the predicted route energy consumption. For the full-mass T70110 case ($E_l = 17.853$ kWh), varying $K_v = 1.37$ by $\pm 10\%$ (1.233–1.507) changes the calculated consumption to 16.068–19.638 kWh. The same relative perturbation of $K_{stop} = 1.08$ (0.972–1.188) gives the same range. If both coefficients vary simultaneously by $\pm 10\%$, energy consumption changes to 14.461–21.602 kWh ($-19\%/+21\%$). Thus, coefficients farther from unity explain a larger share of the correction from the baseline, whereas equal relative uncertainty in any single coefficient has the same local proportional effect. This illustrative assessment does not replace a comprehensive global sensitivity and uncertainty analysis considering the full coefficient ranges, correlations, and interactions, which remains a direction for future work.

Limitations

The proposed methodological approach has several limitations that should be considered when interpreting the obtained results and during the further practical application of the model.

The model is simplified and engineering-oriented in nature and is based on the use of generalized correction factors. The proposed correction factors were not calibrated using a single comprehensive experimental dataset. Instead, their recommended values were established through a synthesis of recent experimental and empirical studies reported in the scientific literature. Therefore, they should be regarded as engineering recommendations intended to improve preliminary energy consumption assessment under limited telematics availability rather than as universally calibrated parameters. This approach is convenient for preliminary assessment of electric energy consumption under limited availability of input data; however, its accuracy largely depends on the correct selection of the coefficients accounting for speed conditions, road conditions, passenger load, temperature, auxiliary systems operation, and stop patterns. In real operation, these factors may change simultaneously and may have nonlinear interrelationships, which are not fully captured by the multiplicative structure of the model.

The adequacy of the model was verified using a limited sample of trolleybus models and control routes. The experimental validation primarily assessed the influence of vehicle mass on electric energy consumption, since reliable control test data under different loading conditions were available for these vehicles. The remaining operational factors, including speed conditions, route profile, ambient temperature, auxiliary systems operation, and stop density, were not validated experimentally within this study. Their influence was incorporated through correction factors derived from published experimental evidence. Consequently, additional validation using comprehensive operational datasets covering a wider range of operating conditions is required.

The experimental validation was based on certified control-test results obtained from an accredited testing laboratory. Three control runs were performed for each test condition, and the official test protocol reports the arithmetic mean of these runs as the certified test result. Since the individual measurement records are not included in the published

protocol, statistical indicators such as standard deviation or confidence intervals could not be determined within the scope of the present study.

Furthermore, the proposed methodology was validated using certified test results obtained for one representative trolleybus model and one reference operating route. Validation using different vehicle types, route characteristics, and operational conditions is required to further assess the robustness and general applicability of the proposed methodology.

In addition, the proposed correction coefficients are assumed to be independent for the purposes of the simplified engineering methodology, although minor interactions may exist between certain operational factors. In particular, ambient temperature affects not only the overall energy consumption represented by K_t , but also the efficiency of regenerative braking, which is partially reflected in K_{stop} . Quantifying these interactions requires dedicated experimental investigations and may be considered in future refinements of the proposed methodology.

The present study does not explicitly consider the uncertainty of input data or the sensitivity of the results to changes in individual coefficients.

The present study includes only the illustrative local sensitivity check described above. It does not explicitly quantify uncertainty in the input data, probability distributions of the coefficients, correlations among operational factors, or global sensitivity across the full parameter space.

Thus, the proposed model should not be regarded as a universal high-precision prediction model. Instead, it represents a simplified engineering methodology intended for preliminary assessment of electric energy consumption when detailed telematics, long-term operational measurements, or extensive experimental datasets are unavailable. Future research should focus on systematic calibration and validation of the correction factors using large-scale operational data collected under controlled variations in individual operating conditions.

5. Conclusions

This article proposes a methodological approach to estimating the specific electric energy consumption of urban electric buses under different operating conditions. Its distinctive feature is the combination of a baseline energy consumption value, determined from a driving cycle or vehicle specification data, with a system of correction factors that account for average speed, road conditions and route profile, vehicle mass, temperature conditions, auxiliary systems operation, and the number of stops, accelerations, and braking events. This approach makes it possible to adapt the calculation to the real operating conditions of urban public transport and to increase the practical value of the results compared with the use of standardized driving cycles alone.

It was established that baseline-specific electric energy consumption values cannot fully characterize the actual energy consumption of an electric bus on a route, since real operating conditions significantly change the load on the traction system and auxiliary consumers. The greatest influence on changes in specific consumption is exerted by average speed, the intensity of acceleration–braking modes, temperature conditions, and passenger load. A decrease in average speed to a level typical of congested urban traffic, as well as an increase in the number of stops, leads to a noticeable increase in specific energy consumption, even in the presence of regenerative braking.

Based on the calculation results for electric buses of different mass categories, it was determined that, under baseline conditions, specific electric energy consumption may range approximately from 0.95 to 1.55 kWh/km, depending on the full mass of the vehicle. For a typical urban route with an average speed of about 20 km/h and frequent stops, these values increase to 1.41–2.29 kWh/km. Under difficult operating conditions, particularly under unfavorable temperatures, a more complex route profile, and increased auxiliary

system load, specific consumption may reach 2.58–4.21 kWh/km. This confirms the need for a differentiated approach to assessing electric bus energy consumption, considering the mass category and operating scenario.

Verification of the proposed approach using the example of control route No. 15 in Lutsk showed acceptable agreement between calculated and actual values. For a vehicle with a full mass of approximately 19 t, the calculated electric energy consumption was 17.853 kWh over a route length of 10.2 km, corresponding to a specific value of approximately 1.75 kWh/km. This indicates the possibility of using the proposed model for preliminary engineering assessment of electric energy consumption by urban electric transport in the absence of a complete set of telematics or experimental data.

Comparison of the obtained results with recent literature data confirmed that the calculated values fall within the ranges characteristic of real electric bus operation. This makes it possible to consider the proposed model as an intermediate tool between standardized test cycles and complex prediction models based on large volumes of operational data or machine learning methods.

Although the experimental verification was performed using certified trolleybus test results, the similarity of vehicle mass, passenger capacity, and urban operating conditions supports the use of the proposed methodology for preliminary assessment of battery electric buses. Nevertheless, dedicated validation using experimental battery electric bus data remains an important direction for future research.

The scientific novelty of the study lies in the substantiation of a simplified engineering model for adjusting the specific electric energy consumption of urban electric transport, suitable for application under limited availability of telematics data. The model underwent preliminary validation based on control tests of vehicles with different masses, confirming the possibility of its use for engineering assessment of energy consumption under real operating conditions.

Further research should focus on refining the correction factors based on an expanded sample of actual operating data for electric buses of different classes, seasons, route types, and road conditions. Special attention should be paid to accounting for regenerative braking efficiency, the operation of heating, ventilation, and air conditioning systems, battery degradation, driving style, and the influence of traffic congestion. This will improve the accuracy of the model and expand its applicability for predicting the energy consumption of urban electric transport.

The proposed methodology should be regarded as a practical engineering tool for preliminary energy consumption assessment rather than a universal high-precision prediction model. It complements rather than replaces advanced telematics- and machine-learning-based prediction approaches in situations where detailed operational datasets are unavailable.

Future research will focus on statistical calibration of the correction coefficients and quantitative sensitivity analysis using large-scale operational datasets collected under different climatic and operating conditions.

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