HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

ANALYSIS OF THE GENERAL DESIGN, OPERATING PRINCIPLE, AND OPERATIONAL PERFORMANCE OF ELECTRIC BUSES

Ortikov Sarvar Sattaraliyevich
Fazliddinov Salohiddin Sadriddin ugli
Andijan State Technical Institute, Andijan, Uzbekistan
Doi: https://doi.org/10.5281/zenodo.22852496

Abstract. This article analyzes the general design, main units and systems, operating principle, and operational indicators of modern electric buses. The principle of interaction between the traction electric drive of the electric bus, the high-voltage battery, the inverter, the electric motor, the gearbox, the regenerative braking system, the onboard charging device, control electronics, and auxiliary consumers is considered. A systematic analysis was conducted on the influence of speed, acceleration and braking modes, passenger mass, longitudinal road gradient, external temperature, auxiliary device power, and driving conditions on the operational efficiency of electric buses. Additionally, energy consumption, mileage reserve, battery charge state (SOC), technical readiness coefficient, regenerative braking efficiency, and kWh/km indicators were substantiated as the primary criteria for electric bus operation. The research results can serve as a theoretical basis for the digitalization of electric bus operating processes, energy consumption forecasting, and control based on Digital Twin technology.

Keywords: electric bus, electric car, electric drive, battery, electric motor, inverter, SOC, SOH, energy consumption, regenerative braking, performance indicator, Digital Twin.

Login. Issues of increasing energy efficiency in the global transport system, reducing harmful atmospheric emissions, and ensuring the environmental sustainability of urban public transport necessitate the expansion of the use of electric vehicles. In particular, the electrification of bus routes with high frequency in passenger transportation is one of the promising directions for increasing the energy efficiency of the transport system.

Unlike a conventional bus with an internal combustion engine, the electric bus drives energy not through the combustion of chemical fuel, but by converting electrical energy stored in a high-voltage battery into mechanical energy through an electric drive. Therefore, when evaluating the operational efficiency of an electric bus, it is necessary to consider not only transport performance but also electricity consumption, battery charging levels, regenerative braking, the environment, and driving conditions.

In the practical operation of electric buses, energy consumption is not a constant value. It varies depending on route length, speed, number of accelerations, stops, number of passengers, road gradient, traffic, outdoor temperature, and air conditioning or heating system performance. Therefore, the collection, analysis, and forecasting of real-time data are of great importance in managing electric bus operation.

This issue also provides an important theoretical basis for the future use of **Digital Twin** technology that connects the real object of an electric bus with a virtual model.

An electric bus is a passenger transport vehicle that uses electricity for movement, the design of which is based on the mutual integration of mechanical, electrical, electronic, and information systems.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

The general design of a modern electric bus can be divided into the following main systems:
1. high-voltage battery;
2. electric traction motor;
3. inverter;
4. gearbox or transmission;
5. regenerative braking system;
6. Battery Management System (BMS);
7. onboard charging device;
8. DC/DC converter;
9. control electronics system;
10. auxiliary electrical consumers;
11. braking and control systems;
12. Telematics and monitoring systems.

The structural diagram of the electric bus can be expressed in a simplified form as follows:

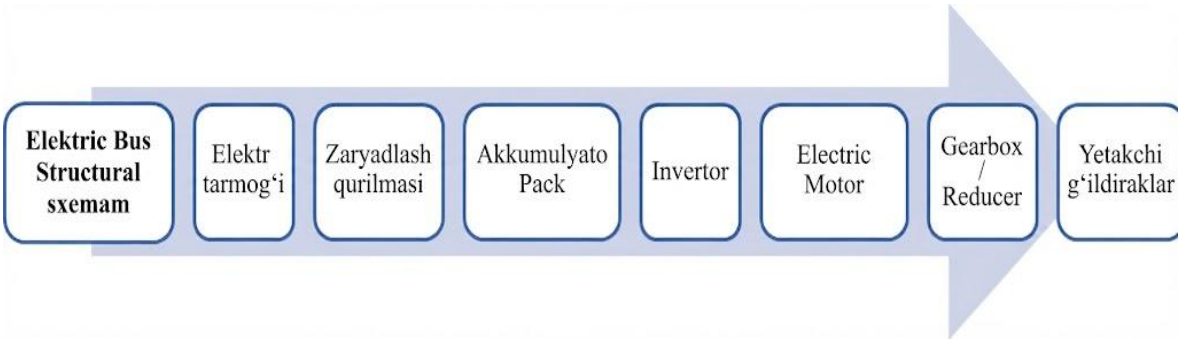


Figure 1. Design diagram of an electric bus.

In parallel with this:

Accumulator → DC/DC converter → 12/24 V systems → Auxiliary consumers a circuit is available.

One of the most important structural elements of an electric bus is a high-voltage battery. It stores electrical energy and provides the traction electric drive with the necessary power. Battery capacity directly affects the mileage, mass, charging frequency, and operational efficiency of the electric bus.

The Battery Management System **(BMS)** plays an important role in managing the battery system. The BMS monitors the voltage, current, temperature, charging status, and other parameters of the battery cells. Additionally, the system performs functions to protect the battery from overcharging, excessive discharge, and excessive temperature.

The electric motor converts the electrical energy from the battery into mechanical energy and ensures the movement of the electric bus.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr



Figure 2. General design and diagram of the main parts of the electric bus.

The operating principle of an electric bus can be viewed as the conversion of energy from one type to another.

On the go:

$$Ebat \rightarrow Eel \rightarrow Emex \rightarrow Ekin \ (1)$$

energy exchange occurs in the form of.

Here:

E_{bat} — energy stored in the battery;

E_{el} — electrical energy;

E_{mex} — mechanical energy of the electric motor;

E_{kin} is the kinetic energy of the electric bus.

When the driver presses the accelerator pedal, the control system determines the required torque. The inverter converts the direct current from the battery into the electrical mode required for the electric motor. The torque generated by the electric motor is transmitted to the driving wheels via a gearbox or a corresponding transmission.

The tractive force of an electric bus can be estimated using the following general expression:

$$Ft = Fr + Fa + Fg + Fi \ (2)$$

here:

F_r — rolling resistance;

F_a - aerodynamic resistance;

F_g — road slope resistance;

F_i is the inertia resistance.

Rolling resistance:

$$Fr = mgf \ (3)$$

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Aerodynamic resistance:

$F_a = 1/2\ \rho C_d\ AB^2$ (4)

Road gradient resistance:

$Fg = mg\sin\theta$ (5)

Force of inertia:

$Fi = ma$ (6)

It can be seen from these equations that the energy consumption of an electric bus is closely related to its speed, mass, acceleration, and road conditions.

The operating principle of regenerative braking.

One of the important advantages of an electric bus compared to an internal combustion engine bus is the possibility of using regenerative braking.

When the electric bus slows down, the electric motor can switch to generator mode. As a result, part of the mechanical energy of the wheels is converted into electrical energy and returned to the battery.

Progress:

$Ekin \rightarrow Emex \rightarrow Eel \rightarrow Ebat$ (7)

can be expressed as.

Regenerative braking efficiency:

$\eta reg = Ereg/Ekin \times 100\%$ (8)

can be evaluated using the expression.

The importance of regenerative braking increases further due to the large number of stops, frequent acceleration, and braking in city buses.

At the same time, the amount of energy recovered from regenerative braking depends on the SOC state of the battery, speed, braking intensity, and the control algorithm.

Main performance indicators of electric buses.

Several basic technical and energy indicators are used to evaluate the operation of an electric bus.

Table 1.

Main operational indicators of the electric bus

№	Indicator	Designation	Content
1.	Energy consumption	*E*	Electricity consumed
2.	Specific energy consumption	*e*	kWh/km
3.	Running reserve	L_{max}	Distance covered per charge
4.	Battery charge	*SOC*	Current state of charge

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

5.	Battery health	*SOH*	Battery technical condition
6.	Average speed	V_{Avg}	Average speed on route
7.	Maximum speed	V_{max}	Maximum allowed speed
8.	Passenger capacity	*N*	Concurrent passengers
9.	Regenerative energy	E_{reg}	Braking energy
10	Technical training	K_t	Share of electric buses ready for operation
11.	Charging time	t_z	Battery charging duration
12	Operating expenses	C_e	Vehicle usage cost

Specific energy consumption:

$$e=E/L \quad (9)$$

here:
E — consumed electricity, kWh;
L is the distance traveled, km.

This indicator is one of the most important criteria for comparing the energy efficiency of electric buses.

Analysis of factors affecting energy consumption.

The energy consumption of an electric bus is formed as a result of the interaction of many factors.

They can be divided into the following groups:

Technical factors:

Mass of the electric bus, electric motor efficiency, battery capacity, SOH state of the battery, technical condition of the tires, aerodynamic resistance.

Operational factors:

Average speed, number of accelerations, number of brakes, stops, number of passengers, route length.

Road conditions:

The slope of the road, the pavement, the turns, the traffic.

Natural and climatic factors:

External temperature, wind, precipitation.

Auxiliary energy consumers:

Air conditioning, heating, lighting, ventilation, multimedia, compressor.

Therefore, the total energy consumption of an electric bus can be expressed as follows:

$$Eum = Etr + Eaux + Eclim - Ereg \quad (10)$$

Here:
E_{tr} — energy consumed for traction;
Eaux - power consumption of auxiliary devices;
Eclim - consumption of heating and cooling systems;
E_{reg} is the energy returned by regenerative braking.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

This model is convenient for expressing the energy balance of electric bus operation.

Significance of SOC and SOH indicators in operation.

When operating electric buses, it is important to constantly monitor the battery status.

SOC (State of Charge) — the ratio of the available battery charge to the rated capacity.

In a simplified form:

$$SOC = Q_{available} / Q_{nominal} \times 100\% \quad (11)$$

is defined as.

SOH (State of Health) which represents the current technical condition of the battery:

$$SOH = Q_{actual} / Q_{nominal} \times 100\% \quad (12)$$

As the SOH value of the battery decreases, its practical capacity decreases, and as a result, the distance traveled by the electric bus on a single charge can be reduced.

Therefore, when managing the operation of an electric bus, it is necessary to consider not only the current SOC but also the battery's SOH indicator.

The necessity of digitizing operational indicators.

In a traditional operating system, many electric bus indicators can be recorded in separate systems. However, in modern transport management, it is important to combine information from various sources into a single digital environment.

In this case, it is advisable to integrate the following data:

GPS/GNSS + CAN-Bus + BMS + IoT + GIS + weather data + passenger flow

Based on this data, a digital model of the current state of the electric bus can be formed.

This approach allows for the implementation of **Digital Twin** technology at the next stage.

The Digital Twin model in general:

$$DT = f(V, a, m, N, T, I, SOC, SOH, P_{aux}, L) \quad (13)$$

can be expressed as.

In this model, the technical and operational parameters of the real electric bus are constantly updated, and the state of the virtual model is adapted to the real object.

Results and their discussion.

The conducted analysis shows that the operational efficiency of an electric bus is not determined solely by the technical performance of the electric motor or battery. It is formed under the complex influence of technical, transport, road, climatic, and administrative factors.

The formation of electric bus energy consumption can be expressed through the following conceptual connection:

$$E = f(V, a, N, m, i, T, L, SOC, SOH, P_{aux}, E_{reg}) \quad (14)$$

Based on this relationship, the following three main directions can be identified in managing the operation of electric buses:

1. Monitoring - determining the real condition of the electric bus.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

2. Forecasting — predicting future energy consumption, SOC, SOH, and technical condition.

3. Optimization - determining the management mode that reduces energy consumption and operational costs.

Thus, the transition from monitoring to forecasting and from forecasting to optimal management of electric bus performance indicators is one of the main directions for the development of the modern digital transport system.

Elements of scientific novelty.

Within the framework of this article, the following scientific conclusions were formulated:

1. To evaluate the operational efficiency of electric buses, the need for comprehensive consideration of technical, energy, transport, road, and climatic factors was substantiated.

2. An energy balance model has been proposed, representing the total energy consumption of an electric bus through traction, auxiliary devices, climate systems, and regenerative braking components.

3. To digitalize the operation of electric buses, it is necessary to integrate GPS/GNSS, CAN-Bus, BMS, IoT, and GIS data into a single information environment.

4. A set of basic parameters for managing electric bus operation processes based on Digital Twin technology:

$$DT = f(V, a, m, N, T, i, SOC, SOH, P_{aux}, L) \quad (15)$$

was formed in the form.

Conclusion. According to the research results, the overall structure of electric buses consists of mutually integrated systems that serve to store, control, convert into mechanical energy, and ensure movement.

During the operation of the electric bus, the battery, BMS, inverter, electric motor, transmission and regenerative braking systems work in close connection with each other. The technical condition of these systems directly affects the energy efficiency and operational reliability of the electric bus.

The analysis showed that the electric bus's specific energy consumption (kWh/km), mileage reserve, SOC, SOH, regenerative energy, technical readiness coefficient, and charging time are important indicators evaluating its operational efficiency.

And energy consumption:

$$E = f(V, a, N, m, i, T, L, SOC, SOH, P_{aux}, Ereg) \quad (16)$$

can be characterized by a multifactorial relationship in the form of.

Based on this, a promising direction for managing electric buses consists of collecting real-time data, analyzing it, forecasting the operational state, and forming optimal management decisions.

In particular, integrating GPS/GNSS, CAN-Bus, BMS, IoT, GIS, and artificial intelligence technologies into the **Digital Twin** platform is a promising scientific and practical direction for monitoring electric bus operation processes, predicting energy consumption, assessing the technical condition of the battery, and increasing management efficiency.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

References

1. Ehsani M., Gao Y., Longo S., Ebrahimi K. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*. CRC Press.
2. Larminie J., Lowry J. *Electric Vehicle Technology Explained*. Wiley.
3. Husain I. *Electric and Hybrid Vehicles: Design Foundations*. CRC Press.
4. Emadi A. *Advanced Electric Drive Vehicles*. CRC Press.
5. *Electric and Hybrid Vehicles: Technologies, Modeling and Control.* Wiley.
6. Chan C.C. The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*.
7. Tie S.F., Tan C.W. A review of energy sources and energy management systems in electric vehicles. *Renewable and Sustainable Energy Reviews*.
8. Reif K. *Fundamentals of Automotive and Electric Vehicle Technology*. Springer.
9. International Energy Agency. *Global EV Outlook*. Paris: IEA.