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Assessment of the life cycle of city buses with diesel and electric drive in the operation phase

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The aim of the article is to analyze the impact of operation on the life cycle assessment of city buses with diesel and electric drive using neural networks based on source data. Two types of diesel buses and two types of electric buses were tested. As a result of the conducted tests, the following optimal values were obtained for buses: operation time, number of inspections, daily refueling time or battery charging time, general efficiency, emissions. The adopted values of the life cycle assessment criteria are optimal for electric and electric city buses. The presented research and analyzes have a significant impact on the processes related to the organization of public transport.

Key words: *life cycle assessment, city buses, neural networks, diesel drive, electric drive*

1. Introduction

The aim of the article is to analyze the impact of operation on the life cycle assessment of city buses with diesel and electric drive using neural networks based on source data. Solaris buses are used in many Polish cities Life Cycle Assessment (LCA) concerns the assessment of potential threats to the environment. The vehicle operation phase will be analyzed. The following evaluation criteria were used:

- material and economic criterion: duration of operation
- number of inspections, daily refueling or battery charging
- time
- energy criterion: overall efficiency
- environmental criterion: emissions of harmful substances.

2. Literature review

The application of the LCA cycle and issues related to buses have been presented in many publications. Publication [13] presents the CO_2 emissions of vehicles with internal combustion and electric drives using LCA. CO_2 emissions during battery production are taken into account. Publication [11] presents two cars, one with a combustion engine and the other with an electric drive. LCA was used for the analysis. Studies have shown that the electricity supplied today in Italy for electric vehicles is, and is likely to be in 2030, mainly generated by fossil fuel power plants. Publication [15] presents a case study and a model for predicting maintenance interventions based on monitoring the condition of engine oil in city buses with internal combustion engines. Publication [21] developed a modeling framework for optimizing electric bus charging schedules that determines both planning and operational decisions while minimizing total annual costs. Comparative analyzes have shown that it is more economical and environmentally friendly to use electric buses than diesel buses. Publication [10] presents a model of longitudinal dynamics for calculating the energy demand for electric buses. The results of the model should serve as the basis for further research into battery sizes, charging strategies and charging infrastructure requirements. Publication [6] presents the results of research on the impact of various forecasted scenarios of modernization of urban bus transport in Krakow on air pollutant emissions. The implementation of the assumed scenarios, consisting in replacing old buses with modern, low- or zero-emission vehicles, will reduce the emission of nitrogen oxides (NO_x) by over 60%, volatile organic compounds (VOC) by over 82%, and carbon monoxide (CO) by nearly 52%, and particulate matter from fuel combustion (PM_{ex}) by over 77% by 2025. Studies also show an increase in N_2O emissions (by almost 43%) as a result of modernization. This phenomenon is characteristic of modern engines. In addition, the introduction of electric buses into the fleet contributes to the gradual reduction of benzo(a)pyrene emissions. Although the replacement of the bus fleet is a long-term and costly process, such actions are necessary for Krakow and the surrounding municipalities to improve air quality in this area, especially due to excessive concentrations of particulate matter and nitrogen oxides. Publication [18] presents research on trolleybuses, diesel hybrids and e-buses, including fuel cell buses. These electric city buses were compared with combustion engine vehicles represented by diesel and CNG (compressed natural gas) buses in terms of energy consumption and costs, greenhouse gas emissions, noise costs and life cycle. The results show that electric buses are a promising means of urban transport. Publication [14] presents an analysis of the life cycle costs of a fleet of electric city buses on various routes of operation. The goal is to determine the charging and battery power requirements, as well as energy consumption and life cycle costs. A special simulation tool has been developed for comprehensive evaluation of electric buses under various operating conditions. The tool allows you to systematically generate and simulate various operating scenarios with the selected bus configuration, charging method and operating route. Publication [17] presents a way to achieve a balance between diesel and electric buses. To achieve this goal, real-world bus network data in Porto, Portugal was studied, and an evolutionary algorithm developed mixed-fleet solutions, with a brief sensitivity analysis that gave an overview of how to improve performance. Publication [7] presents the impact on the sustainable development of electric buses, noise, energy consumption and costs. In Sweden, the number of electric buses is increasing, contributing to the development of a society free of fossil fuels and reducing emissions. Previous studies of bus systems have shown the need for further study of social costs, total cost of ownership, annualized energy consumption to account for seasonal variations and acceleration noise. Addressing these needs was the aim of this study. Publication [9] developed a mathematical model of urban bus transport to support the implementation of charging infrastructure. The novelty of the model is that it includes infrastructure elements for both static and dynamic charging technologies at the same time. Publication [8] presents a European vision of more environmentally friendly buses. The innovations introduced engines with lower fuel consumption and improved the electric drive. Publication [1] presents technical and economic problems related to the implementation of buses with electric and hydrogen drives. Publication [19] presents an analysis of the total cost of ownership (TCO) of city buses with hybrid and diesel electric drives for selected urban and suburban cycles. The results show that the route and daily trips have a significant impact on the total cost of ownership values. These two factors significantly affect the total cost of the vehicle, regardless of the type of drive. In addition, it was shown that the costs of owning and operating a city bus depend on the type of drive system. The TCO method made it possible to estimate the value of the individual cost of components that make up the purchase of the vehicle and the operating costs. The test results show that electric buses represent the highest TCO values among the analyzed vehicles. Publications [2, 12, 20] present issues related to electric buses. Publication [5] presents a comparative analysis of life cycle emissions of carbon dioxide emitted by electric vehicles using different energy mixes and vehicles with an internal combustion engine. Publication [4] presents an economic analysis of electric vehicles in Poland. Publication [3] presents an analysis of the energy consumption of a hybrid drive system of a passenger car in real road conditions.

The presented publications did not apply the life cycle assessment criteria described in the article for city buses.

3. Research methodology

As part of the life cycle assessment criteria, two types of combustion buses and two types of electric buses were analyzed, taking into account their propulsion sources. The duration of operation was determined on the basis of publication [26]. The inspection of the bus should take place every six months [27]. The time of one-time charging of an electric bus with the use of a pantograph is 20 minutes [23]. The single refueling time of a diesel bus is 10 minutes [24]. Overall efficiency was determined on the basis of publications [22, 25]. Emissions of harmful substances while driving for diesel buses are 1, and for electric buses 0. In Table 1 presents the technical data of the Solaris Urbino 12 bus.

Table 2 presents the technical data of the Solaris Urbino 18 bus. Figure 1 shows the Solaris Urbino 18 bus. Table 3 presents the technical data of the Solaris Urbino 12 Electric bus.

Table 1. Technical data of the Solaris Urbino 12 bus [16, 28]

Type of Solaris Bus	Urbino 12
Years of production	Since 1999
Doors layout	2-2-2 2-2-0 1-2-2 1-2-0
Engines	1) Cummins ISB6.7E6C 250B 2) Cummins ISB6.7E6C 280B 3) Cummins ISB6.7E6C 300B 4) DAF MX-11 210 5) DAF MX-11 240 6) DAF MX-11 271
The power of the engines	1) 189 kW (257 HP) 2) 209 kW (284 HP) 3) 224 kW (304 HP) 4) 210 kW (286 HP) 5) 240 kW (326 HP) 6) 271 kW (368 HP)
Transmission	1) ZF-EcoLife 2) Voith DIWA.6

Table. 2 Technical data of the Solaris Urbino 18 bus [16, 28]

Type of Solaris Bus	Urbino 18
Years of production	Since 1999
Doors layout	2-2-2-0 2-2-2-2 1-2-2-0 1-2-2-2
Engines	1) DAF MX-11 240 2) DAF MX-11 271
The power of the engines	1) 240 kW (326 HP) 2) 271 kW (368 HP)
Transmission	1) ZF-EcoLife 2) Voith DIWA 6

Fig. 1. Solaris Urbino 18 bus

Table. 3 Technical data of the Solaris Urbino 12 Electric bus [28]

Type of Solaris Bus	Urbino 12 Electric
Years of production	Since 2013
Doors layout	2-2-2 2-2-0 1-2-2 1-2-0
Engines	1) asynchronous motor TSA TMF 35-28-4 2) in axis ZF AVE130 350V 3) ZF AVE130 400V option
The power of the engines	1) 160 kW 2) 120 kW 3) 125 kW

Table 4 presents the technical data of the Solaris Urbino 18 Electric bus.

Table 4. Technical data of the Solaris Urbino 18 Electric bus [28]

Type of Solaris Bus	Urbino 18 Electric
Years of production	Since 2014
Doors layout	2-2-2-2 2-2-2-0 1-2-2-2 1-2-2-0
Engines	1) Central asynchronous motor TSA TMF 35-44-4 2) ZF AVE 130 option
The power of the engines	1) 160 kW 2) 2*120 kW 3) *125 kW

Fig. 2 shows the Solaris Urbino 18 Electric bus. Neural networks were used to determine the optimal values of the adopted life cycle assessment criteria.

Fig. 2. Solaris Urbino 18 Electric bus

Table. 5 data summary for optimizing the life cycle assessment of buses

No.	Bus	Duration of operation [years]	Number of reviews	Daily refueling or battery charging time [min]	Overall effi-ciency [%]	Emis-sions
1	Solaris Urbino 18	14	28	10	40	1
2		13	26	10	40	1
3		12	24	10	40	1
4		11	22	10	40	1
5		10	20	10	40	1
6		7	14	10	40	1
7		3	6	10	40	1
8	Solaris Urbino 18 Electric	1	2	40	90	0
9	Solaris Urbino 12	13	26	10	40	1
10		11	22	10	40	1
11		10	20	10	40	1
12	Solaris Urbino 12 Electric	0	1	40	90	0

Optimization of the analyzed parameters was carried out using neural networks using the cluster analysis model (Kohonen networks) in the Statistica program.

The following signals are specified:

– quantitative input variables: daily refueling or charging
– time, overall efficiency, emissions
– qualitative input variables: sum of lifetime and number of inspections.

Table 6 shows the prediction sheet. Figure 3 shows the activation histogram. Table 7 presents a list of errors in the cluster analysis model.

Table 6. Prediction sheet

No. – case	Activations
1	0.922341
2	1.071934
3	0.918715
4	0.914997
5	0.911186
6	0.907277
7	0.903268
8	1.269661
9	1.071934
12	1.261194

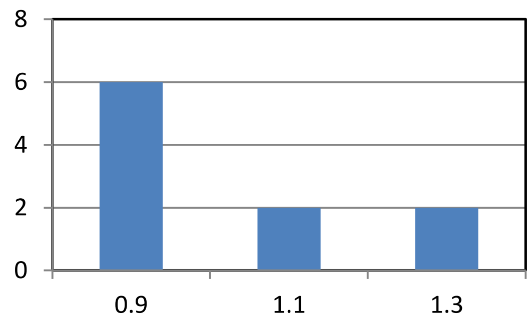

Fig. 3. Activation histogram

Table 7. List of errors in the cluster analysis model

Error (learning)	Error (testing)	Error (validation)
1.071340	0.830259	0.837220

Then, the optimization of the analyzed parameters was carried out using neural networks using a regression model in the Statistica program.

The following signals are specified:

– quantitative input variables: daily refueling or charging,
– time, overall efficiency, emissions,
– qualitative input variables: sum of operation time and number of inspections,
– quantitative output variables: activations of the prediction sheet (Table 6).

Table 8 shows the prediction sheet.

Table 8. Prediction sheet

No. – case	Output
1	1.011498
2	1.010551
3	0.948154
4	0.903268
5	0.903268
6	0.903268
7	0.903268
8	1.273699
9	1.010551
12	1.273699

Figure 4 shows the histogram of the output values.

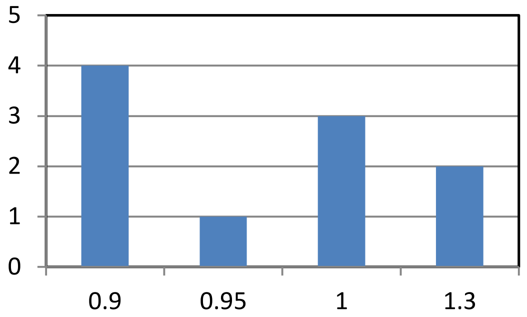

Fig. 4 Histogram of output values

Table 9 shows the list of quality and errors in the regression model.

Table 9. List of quality and errors in the regression model

Quality (training)	Quality (testing)	Quality (validation)	Error (training)	Error (testing)	Error (validation)
0.95645	0	0	0.00083	0.40794	0.40794

4. Research analysis

As a result of using neural networks with a cluster analysis model for buses Solaris Urbino 12 and 18 with diesel drive, the optimal values were for: service life 13 years, number of inspections 26, daily refueling time 10 minutes, overall efficiency 40%, emission 1. for Solaris Urbino 12 Electric buses with electric drive, the optimal values were for: duration of operation 0 (less than one year), number of inspections 1, daily battery charging time 40 min, overall efficiency 90%, emissions 0 and Solaris Urbino 18 Electric with electric drive for: operation duration 1 year, number of inspections 2, daily battery charging time 40 min, general efficiency 90%, emission 0. As a result of using neural networks with a regression model for Solaris Urbino 12 diesel buses, the optimal values were for: operation duration 13 years, number of inspections 26, daily refueling time 10 minutes, overall efficiency 40 %, emissions 1 and Solaris Urbino 18 with diesel drive for: service life 13 and 14 years, number of service intervals 26 and 28, daily refueling time 10 minutes, overall efficiency 40%, emissions 1. For Solaris Urbino 12 Electric buses with drive optimal values were for: operation duration 0 (below one year), number of inspections 1, daily battery charging time 40 min, general efficiency 90%, emission 0 and Solaris Urbino 18 Electric with electric drive for: operation duration 1 year, number of service 2, daily battery charging time 40 min, overall efficiency 90%, emissions 0.

5. Conclusions

On the basis of the conducted tests and analyzes of the life cycle assessment of city buses in the operation phase, taking into account their drive sources, it was shown that the adopted values of the life cycle assessment criteria are optimal for both city buses with diesel and electric drives. Diesel buses have a longer service life and shorter refueling time, but lower overall efficiency and emit harmful substances while driving. Electric buses have a shorter lifespan and longer battery charging times, but they are more efficient overall and do not emit harmful substances while driving. The presented studies and analyzes show that with the current technological development, both diesel and electric buses are used in urban transport. The results of the conducted analyzes have a significant impact on the processes related to the organization of public transport. Further research will be conducted towards the application of other life cycle assessment criteria for various types of urban transport rolling stock.

Nomenclature

CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
LCA	life cycle assessment
NO_x	nitrogen oxides
N_2O	nitrous oxide
TCO	total cost of ownership
VOC	volatile organic compounds

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