ESTIMATION OF THE PUBLIC TRANSPORT OPERATING PERFORMANCE: EXAMPLE OF A SELECTED CITY BUS ROUTE

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Resume

The efficiency of the public transport use is a complex indicator formed from a set of partial assessments of its economic, technical and environmental efficiency. Special attention must be paid to the evaluation of efficiency based on energy consumption, taking into account transport work on the city route. The article is devoted to study of the operation performance of a diesel city bus on the selected city route and determines its energy efficiency by specific fuel consumption per unit of transport work. Based on statistical data, the distribution patterns of the speed and acceleration of the bus on the studied route were determined. The analytical dependence of the specific fuel consumption on the average daily passenger flow capacity on the route is obtained and its adequacy is confirmed. Using the dependence obtained, the fuel consumption of the bus was estimated in individual hauls and a certain section of the route.

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1 Introduction

Sustainable economic development currently emphasizes environmental protection and lower consumption of harmful fossil fuels. According to the EU recommendations, in the long term of transport development, the goal is to achieve climate neutrality [1-2]. However, as of today, it is not yet fully possible. Transport is a field that is largely responsible for the fuel consumption and the emission of harmful substances into the environment [3-4]. One form of transport is a public transport within cities. It can be implemented by various means; the impact on the environment is presented in [5]. Zero-emission measures, such as city bikes and electric vehicles, are the most desirable [6]. In the case of electric vehicles, an important factor is the source of primary energy from which the electricity is generated. Currently, the public transport using fossil fuels dominates in medium-sized cities. In large cities, where there is an extensive metro, tram and city rail system, the share of transport using fossil fuels is smaller. According to data from work [7], diesel buses are still the dominant group of public transport in Europe. As a part of current activities, the effects of which can be seen immediately, public transport is preferred and thus efforts are made to limit individual transport. Activities of this type are implemented in many European cities and examples can be found in [4, 8-9]. Public transport, in addition to reducing the fuel consumption per passenger, contributes to reducing traffic, noise and emissions of harmful pollutants [10]. It also prevents the exclusion of certain groups of society. To demonstrate the benefits that can be achieved in energy consumption through the use of public transport, the article analyzes the fuel consumption necessary to perform transport work, expressed in the number of passengers transported in a given route section. In [11] the characteristics of urban road transport of the transport system are systematized, affecting its energy efficiency and productivity. Such groups of characteristics are considered significant, which describe individual vehicles, traffic flow in general and means of traffic control, as well as road, climatic and weather conditions. Based on expert assessments, ranges of values and implementation options have been identified for each characteristic. Criteria are proposed to evaluate energy efficiency and productivity as target functions of 22 system parameters. The work is theoretical in nature; no experimental studies have been conducted. The continuation of this work was reflected in a study [12], of which, based on statistical criteria, reduced the set of system parameters to a basic set of 10 parameters. The category, type of power plant, age, degree of use of load capacity (passenger capacity) of a vehicle, the level of traffic complexity, the degree of road resistance, the degree of curvature of the roadway, the level of motorization of the city, time interval and weather conditions are defined as basic parameters. The resulting parameter of the system is the level of energy efficiency, which is calculated as the ratio of the energy required for the movement of a vehicle in a given mode on a horizontal road in high gear in moderate weather conditions, to the actual energy consumed. At the same time, correction factors are used that consider the traffic conditions. However, the correction factors have errors that depend on the experience of the experts and the vague presentation of the observational data. Therefore, the question of determining the amount of energy consumption in a given range of accuracy remains open. The results of experimental research of different states of the transport system made it possible to obtain a mathematical model in the form of a linear multiple regression equation to estimate the energy efficiency of transport in urban mobility.

The energy consumption and fuel demand can be determined analytically or based on measurement data. In the work [13], developed mathematical models were used to determine the energy consumption of the traffic. In the presented study, data from the city authorities of Rzeszow and MPK Rzeszow (Rzeszow Urban Transport Company) were used to determine the energy consumption. Those data included information on the daily fuel consumption of a vehicle, its daily mileage and the transported passengers. In addition, data from the remote monitoring system were recorded, containing data on the speed and position of the vehicle. Those data can be collected from the monitoring system described in [14] or from the GPS module itself [13, 15]. The data used are from February and March 2022, that is, the period without pandemic restrictions. Compared to data before the pandemic, passenger transport by public transport in the city of Rzeszow decreased approximately twice. The impact of the pandemic itself on changes in traffic and transport has been described in the literature [16-17]. With a significant decrease in passenger transport, an interesting question is what the data on energy consumption in traffic look like. In the analysis carried out, data on transports with vehicles equipped with a diesel engine were used. These vehicles still represent almost half of the city bus fleet in the city of Rzeszow. The second significant group is the CNG-powered vehicles and the third group is electric buses, which represent approximately 5% of the fleet. Nonlinear models to determine the current fuel consumption, based on the speed and acceleration of vehicles, are presented in [18-19]. However, the model was maintained with the caveat that it should not be used for data outside the scope of a typical vehicle. In [18], microscopic modelling was also used to quantify the dependence of transportation fuel consumption on demand for transport flows, considering the configuration of the transport network. The study was carried out using the example of US transport networks.

The paper consists of six sections. Section 2 describes the study objects and data collection methods. In Section 3, the characteristics of the bus indicators on the studied route are described. Section 4 contains a statistical analysis of fuel consumption indicators; Section 5 shows simulation calculations of specific fuel consumption and energy efficiency of the bus in individual hauls and a certain section of the route. Discussion and conclusions are presented in Section 6.

2 Characteristics of research objects

The city route #13 in the city of Rzeszow (Poland) was chosen as the object of research. The route is shown in Figures 1 and 2.

The total length of the route from A to B is 16.376 km and from B to A is 16.805 km. On the route from A to B there are 35 bus stops and from B to A there are 38 bus stops. The distances between the bus stops are shown in Table 1.

The GPS data was collected using the Teltonika FMB920 intelligent tracker with Bluetooth connectivity (Figure 3). The Teltonika FMB920 specifications are shown in Table 2.

Main characteristics of the studied bus Mercedes-Benz O530 with diesel engine are shown in Table 3.

3 Characteristics of the bus operating indicators on the studied route

Measurement of operational indicators of the Mercedes-Benz O530 bus on the studied route was carried out in 25 working days in the period from 16.02.2022 to 29.03.2022. During the motion and stops of the bus, the data from the GPS receiver on the coordinates (longitude and latitude) of the vehicle were read and recorded in 1 second increments. The speed V and the acceleration a of the bus at each step were determined as the first and second derivatives of the traveled distance, respectively and they are the average speed and the average acceleration during 1 second. Table 4 shows a fragment of the generated data set.

For a typical working day, 70705 bus speed values

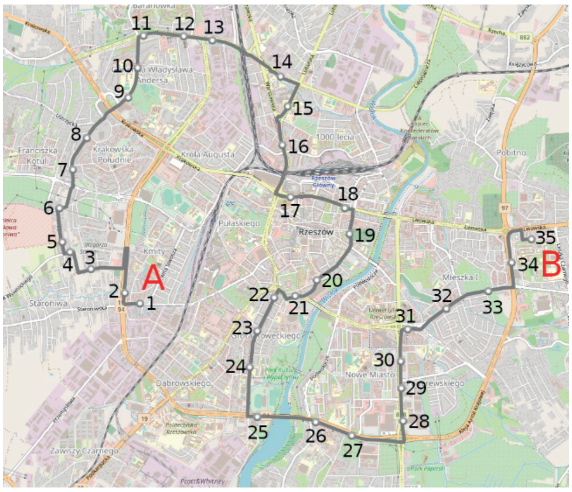


Figure 1 *Bus route #13 from A to B*

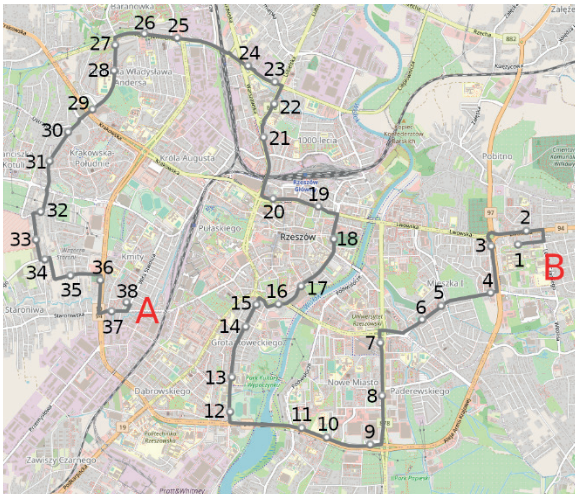


Figure 2 *Bus route #13 from B to A*

Table 1 *Distances between bus stops*

Bus stop number	Distance from previous bus stop m		Bus stop number	Distance from previous bus stop m		Bus stop number	Distance from previous bus stop m	
	A to B	B to A		A to B	B to A		A to B	B to A
1	0	0	14	857	588	27	416	381
2	313	542	15	470	257	28	769	259
3	1064	553	16	484	347	29	352	483
4	416	526	17	711	320	30	288	358
5	182	533	18	607	646	31	412	348
6	400	249	19	299	461	32	497	545
7	465	602	20	693	496	33	490	342
8	399	559	21	343	738	34	528	263
9	630	614	22	326	382	35	445	447
10	333	461	23	395	279	36		388
11	396	298	24	399	329	37		446
12	445	837	25	612	803	38		403
13	309	365	26	631	357			
			sum, m				16376	16805

Figure 3 *Teltonika FMB920 tracker*

__Table 2__ Specifications of Teltonika FMB920 tracker

Module name	Teltonika TM2500
Module technology	GSM/GPRS/GNSS/BLUETOOTH (for external devices)
GNSS	GPS, GLONASS, GALILEO, BEIDOU, SBAS, QZSS, DGPS, AGPS
Cellular technology	GSM
2G bands	Quad-band 850 / 900 / 1800 / 1900 MHz
Data transfer	GPRS Multi-Slot Class 12 (up to 240 kbps), GPRS Mobile Station Class B
Data output	Raw data
Communication with server	GPRS
SIM	Micro-SIM
Memory	128MB internal flash memory
Bluettoth specification	4.0 + LE
Supported bluetooth peripherals	Temperature and Humidity sensor, Headset, OBDII dongle, Inateck Barcode Scanner, Universal BLE sensors support
Receiver	33 channels
Tracking sensitivity	-165 dBM
Position accuracy	< 2.5 m CEP
Velocity accuracy	< 0.1 m/s (within +/- 15% error)
Frequency	1 Hz

__Table 3__ Specifications of Mercedes-Benz O530

Characteristics		Value
Length, m		11.95
Width, m		2.55
Year of production		2012
Passenger capacity	Seating	35
	Standing	55
	Total	90
Engine type		Diesel
Emission standard		EURO V
Average fuel consumption, l*(100km)$^{-1}$		44
Engine capacity, cm^3		6374
Max power, kW		210
Max torque, Nm		1120

__Table 4__ Fragment of a data set

#	Date, time	Longitude	Latitude	Speed V, km·h^{-1}	Acceleration a, m·s^{-2}
1	11.03.2022, 04:24	22.022043	50.069363	4	1.1111
2	11.03.2022, 04:24	22.022106	50.069368	6	0.5556
3	11.03.2022, 04:24	22.022133	50.069380	6	0.0000
4	11.03.2022, 04:24	22.022153	50.069400	7	0.2778
5	11.03.2022, 04:24	22.022170	50.069421	8	0.2778
6	11.03.2022, 04:24	22.022185	50.069448	9	0.2778
7	11.03.2022, 04:24	22.022211	50.069471	10	0.2778
8	11.03.2022, 04:24	22.022253	50.069490	11	0.2778
9	11.03.2022, 04:24	22.022323	50.069506	11	0.0000
10	11.03.2022, 04:24	22.022373	50.069526	12	0.2778

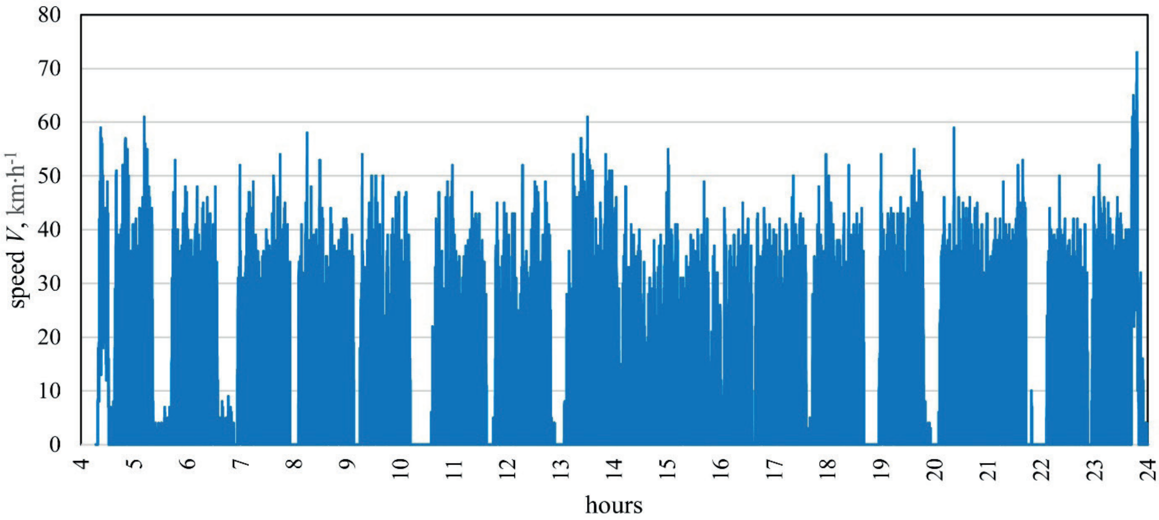


Figure 4 *Bus speed profile during the day*

were obtained in the time interval from 4:19 to 24:00. The bus speed profile, during the day on the route studied, is presented in Figure 4.

To ensure an objective assessment of the parameter studied, the required amount of the experimental sample has been determined according to Equations (1)-(2):

$$N = \frac{t_{\alpha}^{2} \cdot \sigma^{2}}{\eta^{2}} \tag{1}$$

where:
t_{α} - confidence probability function;
σ - standard deviation, km·h^{-1};
η - extreme error allowed, km·h^{-1}.

$$\eta = \Delta \cdot V_{avg} \tag{2}$$

where:
Δ - relative accuracy of accounting; assume $\Delta = 0.01$;
V_{avg} - average value of the speed for the entire working day, km·h^{-1}.

For confidence probability $\theta = 0.95$, function of confidence probability is $t_{\alpha} = 1.96$. As a result is obtained:

$$N = \frac{1.96^{2} \cdot 14.849964^{2}}{(0.01 \cdot 14.14)^{2}} \approx 43000 < 70705$$

Thus, the reliability of the experimental sample is justified.

The values of the bus speed were divided into class intervals, the number of which was determined by the Sturgess's Equation, [20]:

$$k = 1 + 3.32 \cdot \lg(n) \tag{3}$$

where: n - sample size.
$k_V = 1 + 3.32 \cdot \lg(70705) = 17.1$.

After rounding in the larger direction, a value obtained was $k_v = 18$. The size of the class interval λ_V is calculated by:

$$\lambda_V = (V_{\max} - V_{\min})/k \tag{4}$$

where:
V_{max}, V_{min} - the largest and smallest speed values in statistical samples, km·h^{-1}.

$\lambda_V = (73 - 0)/18 = 4.06$.

It is appropriate to assume $\lambda_V = 5$. Furthermore, in the first interval, measurements under conditions $V = 0$, are assigned. Based on this, a new value is defined as $k_v = 16$. Similar indicators of the grouped distribution of acceleration during the day are calculated: $k_a = 18$, $\lambda_a = 0.71$. However, from a practical point of view it is advisable to use $\lambda_a = 1$ and corresponding to it $k_a = 10$. The formation of class groups made it possible instead of 70705 values of each parameter to determine (Table 5) grouped frequencies for each group.

Speeds above 60 km·h^{-1} are possible when the bus is traveling back to the bus depot, but accelerations above 4 m·s^{-2} and decelerations below - 4 m·s^{-2} are probably measurement errors.

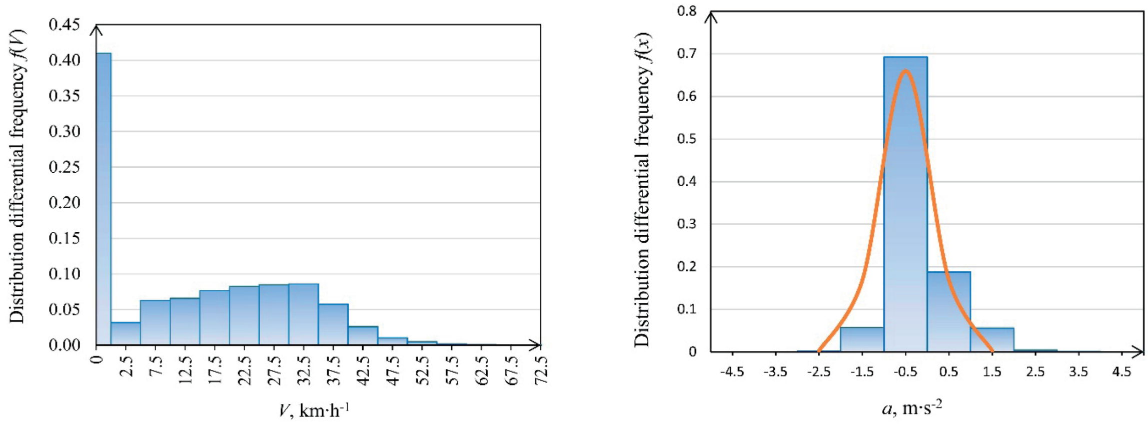
For visual analysis, the distribution graphs of the speed and acceleration of the investigated bus during the day are shown in Figure 5.

Statistical analysis of the speed distribution revealed that the average speed of the bus movement is 23.31 km·h^{-1} and the average speed on the route, considering the time of stops at bus stops and delays in traffic flow, is 14.14 km·h^{-1}. The main part of the acceleration values is in the range [-1,1]. The statistical distribution of acceleration is close to the normal distribution, which, based on the values obtained of the sample average and variance, is described as follows:

$$f(a) = \frac{1}{\sqrt{2 \cdot \pi \cdot 0.366123}} \cdot e^{-\frac{(a - 0.00001)^2}{0.732245}} \approx \approx 0.6593207 \cdot e^{-\frac{a^2}{0.732245}} \tag{5}$$

Table 5 *Results of calculations of the speed and acceleration of the bus interval distributions on the route*

Speed differential frequencies				Acceleration differential frequencies			
i	Value ranges V, km·h^{-1}	absolute m_i	relative f_i	i	Value ranges a, m·s^{-2}	absolute m_i	relative f_i
1	$V_1 = 0$	28971	0.4097	1	$a_1 \le -4$	4	5.66×10^{-5}
2	$0 < V_2 \le 5$	2239	0.0317	2	$-4 < a_2 \le -3$	33	0.000467
3	$5 < V_3 \le 10$	4427	0.06261	3	$-3 < a_3 \le -2$	153	0.002164
4	$10 < V_4 \le 15$	4637	0.06558	4	$-2 < a_4 \le -1$	4040	0.057139
5	$15 < V_5 \le 20$	5420	0.07666	5	$-1 < a_5 \le 0$	48951	0.692327
6	$20 < V_6 \le 25$	5836	0.08254	6	$0 < a_6 \le 1$	13262	0.187568
7	$25 < V_7 \le 30$	5969	0.08442	7	$1 < a_7 \le 2$	3926	0.055526
8	$30 < V_8 \le 35$	6071	0.08586	8	$2 < a_8 \le 3$	271	0.003833
9	$35 < V_9 \le 40$	4060	0.05742	9	$3 < a_9 \le 4$	56	0.000792
10	$40 < V_{10} \le 45$	1824	0.02580	10	$4 < a_{10}$	9	0.000127
11	$45 < V_{11} \le 50$	718	0.01016				
12	$50 < V_{12} \le 55$	320	0.00453				
13	$55 < V_{13} \le 60$	135	0.00191				
14	$60 < V_{14} \le 65$	61	0.00086				
15	$65 < V_{15} \le 70$	14	0.00020				
16	$70 < V_{16} \le 75$	3	0.00004				
	Sum	70705	1		Sum	70705	1
V_{max}=73.0000 km·h^{-1}				a_{max} =7.5 m·s^{-2}			
V_{min} =0 km·h^{-1}				a_{min}= -5.2778 m·s^{-2}			
Average V_{avg} =14.14 km·h^{-1}				Average a_{avg}=0.00001 m·s^{-2}			
Dispersion $D(V)$=220.52143				Dispersion $D(a)$=0.366123			
The standard deviation σ_V=14.849964				The standard deviation σ_a=0.605081			



a b

Figure 5 *Differential distributions of bus speed and acceleration during the day: a - speed, b - acceleration*

The efficiency of urban passenger transport depends on the passenger load of the bus on individual hauls of the transport network. Changes in the passenger traffic parameters cause fluctuations in fuel consumption during the day. In the process of monitoring the dynamics of passenger traffic for 25 days on some sections of route #13, the length of individual hauls, the number of passengers who came and went at the beginning of the haul and the power of the hauls were determined. Based on the data obtained, the volumes of passenger traffic P are calculated (Figure 6), the corresponding transport work performed for each working day of the observation

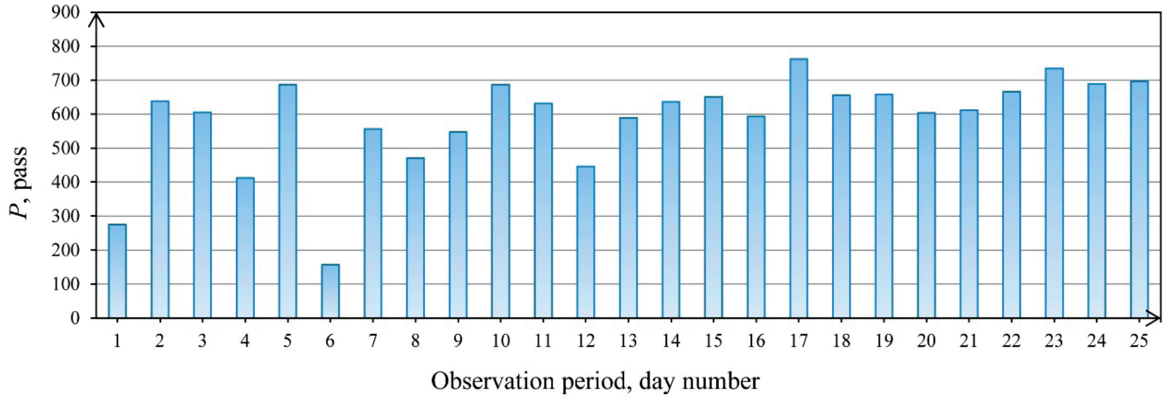


Figure 6 *Daily passenger traffic volumes for the entire observation period*

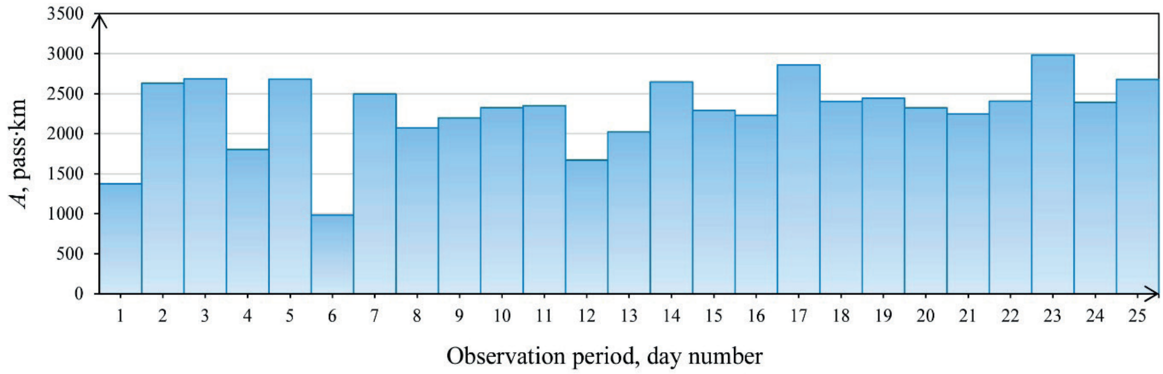


Figure 7 *Transport work performed during the observation period*

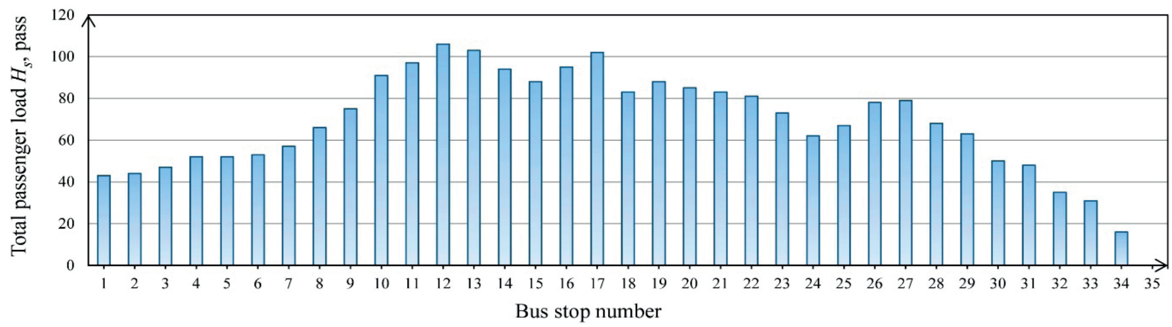


Figure 8 *The total passenger load of the bus on the hauls of the direct trip during the day*

period A (Figure 7) and the average daily passenger load H_{avg}.

Since the parameters P and H_{avg} give only generalized and average estimates of passenger traffic, it is advisable to study the dynamics of changes in their components, depending on the time of day and when performing individual trips.

Figure 8 shows the dependence of the total daily passenger load Hs_i on each haul of a direct trip from A to B, passing through 35 stopping points. The histogram was constructed for the 15th day of the observation period (11.03.2022). In the perspective of passenger traffic analysis, this day is typical, because P_{15} belongs to the class interval with the highest value of the relative differential frequency of distribution: $\max_{1 \le i \le 6} f_i(P) = f(P)_{[650.750]} = 0.4$.

Figure 8 shows that most of the passenger traffic is concentrated in the middle part of the route, which passes through the city center. The Hs_i concentration decreases at the final stops on the route.

To analyze the dynamics of passenger traffic during the day, the working day was divided into six intervals and the total values for each interval were calculated. According to Figure 9 and Figure 10, it can be concluded that the main passenger traffic occurs in the morning, from 6:30 to 9:30.

The dynamics of changes in passenger load on individual trips is similar and repeats the dynamics of the passenger load accumulated on all the trips per day. The histogram of the transport work performed in the time interval from 6:30 to 9:30 for one voyage on a direct trip is shown in Figure 11.

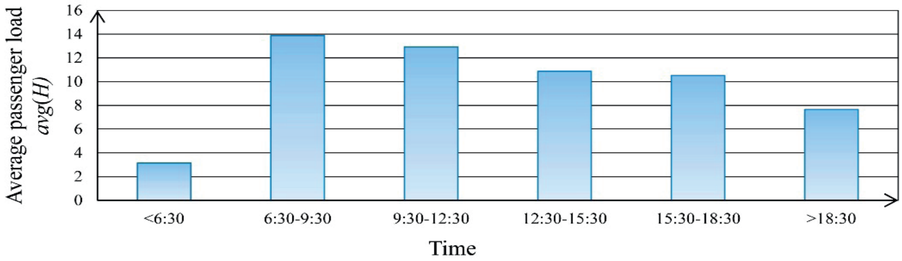


***Figure 9** Average passenger load of the bus according to time intervals*

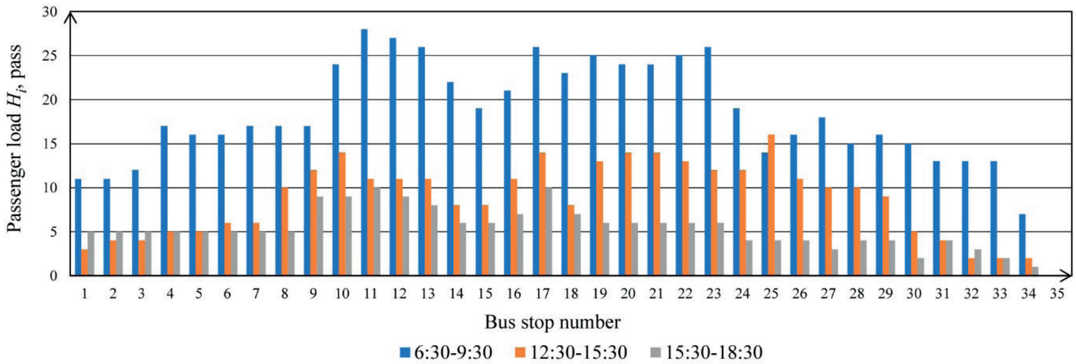


***Figure 10** Passenger load of the bus on direct trip hauls [11.03.2022]*

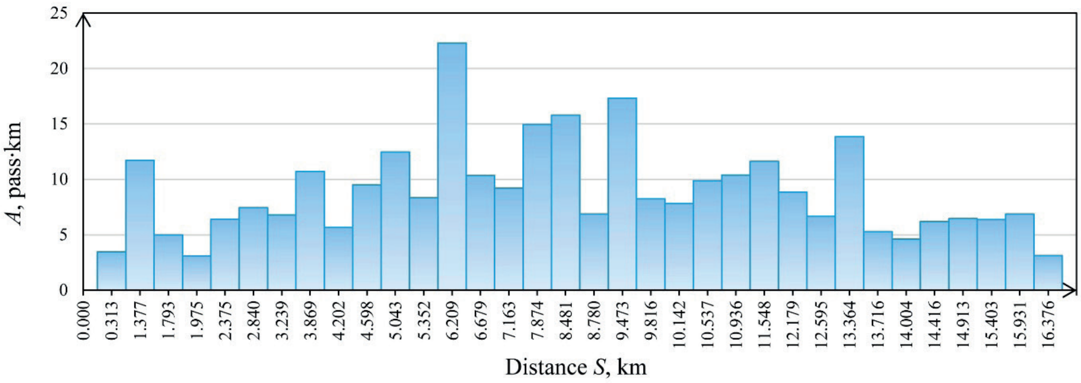


***Figure 11** Transport work on the hauls of the direct trip*

4 Statistical analysis of the bus fuel consumption indicators

To assess the energy efficiency of the passenger transport system as a whole, it is necessary to know the energy consumption for the transportation of passengers in certain sections of the transport network. However, determining the fuel consumption over short periods of time can be complicated and requires specialized equipment. In this study, measurement of the fuel consumption Q was performed once a day at the end of the working day for 25 days. To secure high accuracy of daily fuel consumption the following measures were taken: Urban Transport Company has its own petrol station; only 1 employee of a company is allowed to refuel the bus, this employee always uses the same pump and the same pistol, position of the vehicle must be within 2 m due to fuel hose length, bus had no people onboard - the weight of the vehicle was always the same, during the studied period bus tire pressure was within range of 20 kPa (± 10 kPa from standard pressure). These measures allowed the accuracy of the daily fuel consumption measurement to be within 2%. Based on the measurement data, the fuel consumption per 100 km q is calculated (Figure 12).

A sufficient sample size of 25 is obtained with a relative accuracy of Δ = 0.02 and a confidence level of θ = 0.9. Consumption per 100 km each day of the study period did not exceed 50 l. The distributions of the differential frequencies $f(q)$ and the integral frequencies $F(q)$ are presented in Figure 13.

The number of classes, according to Sturgess's

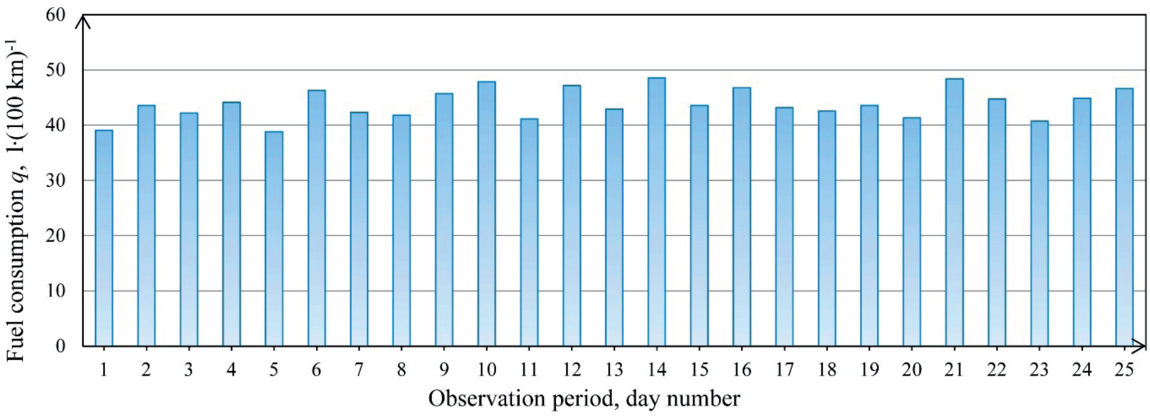


Figure 12 *Fluctuations in fuel consumption q during the study period*

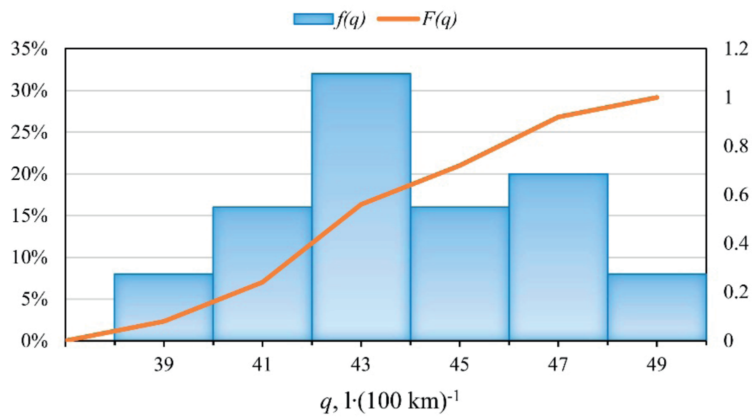


Figure 13 *Distribution grouped by relative frequency of fuel consumption q*

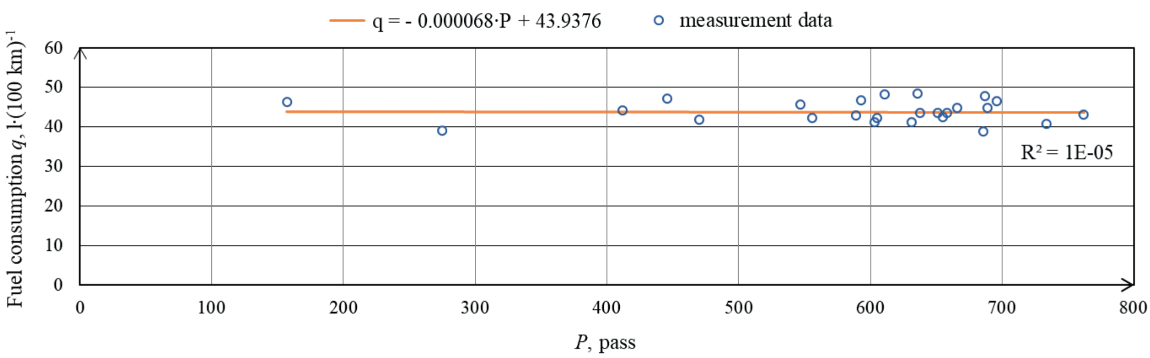


Figure 14 *Course of the average daily fuel consumption per 100 km based on the volume of passengers transported*

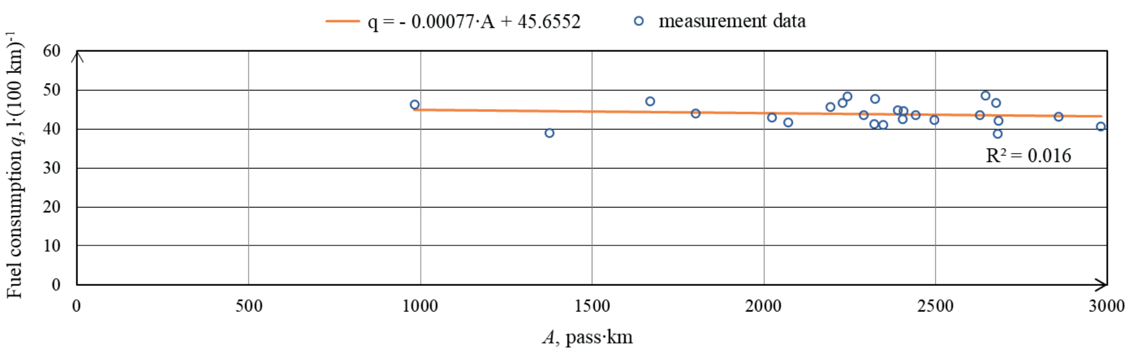


Figure 15 *Course of the average daily fuel consumption per 100 km in transport work*

formula, is 6 and the width of the interval is 2. This distribution has a mathematical expectation μ = 43.9 and a variance σ^2 = 7.27. Accordingly, the standard deviation σ is 2.7. The maximum value of daily expenses is 48.54 l·(100 km)$^{-1}$ and the minimum is 38.78 l·(100 km)$^{-1}$. Most often, the value of fuel consumption is characterized by the mode of distribution Mo = 43 l·(100 km)$^{-1}$.

To estimate the fuel consumption of public transport, graphs were constructed: $q(P)$ taking into account the volume of passengers transported (Figure 14) and $q(A)$ taking into account the transport work performed (Figure 15). Generalized daily values of the necessary indicators for all the periods of supervision were used for construction.

Observation data are approximated by linear dependencies with very small coefficients of determination: $R_1^2 = 10^{-5}$ and $R_2^2 = 0.016$, according to the order of the given graphs, which indicates a lack of relationship between the generalized values of parameters. Furthermore, the issue of determining the fuel consumption in sections of the transport network of arbitrary length remains relevant. As shown in [21], there is a very little impact of passenger load in the range 0 to 1200 kg on the fuel consumption of a public bus.

5 Simulation and estimation of the bus fuel consumption

The fuel consumption Q_i of the passenger transport on the i-th haul is calculated as follows:

$$Q_i = \frac{Q_p \times S_i \times H_i}{1000} \tag{6}$$

where:
Q_p - specific fuel consumption per working day, l·(pass·km)$^{-1}$;
S_i - haul length, m;
H_i - passenger load on the i-th haul, pass.

The specific daily fuel consumption Q_p is proposed as a function of the average daily passenger load H_{avg}. To determine the analytical form of the function $Q_p = f(H_{avg})$, the statistical values of Q_{pj} were approximated, j is the day number in the statistical sample ($1 \le j \le 25$). For the j-th day, Q_{pj} is calculated by the expression (Table 6):

$$Q_{pj} = \frac{Q_j}{A_j} \tag{7}$$

Table 6 *Initial data for modeling*

j	Date	$H_{avg\,j}$, pass	A_j, pass ·km	Q_j, l	Q_{pj}, l·(pass·km)$^{-1}$
1	16.02.2022	4.6979	1374.864	117.14	0.085
2	17.02.2022	9.0225	2629.396	129.82	0.049
3	18.02.2022	9.0690	2683.914	125.68	0.047
4	21.02.2022	6.1097	1801.674	131.85	0.073
5	22.02.2022	9.1994	2680.839	115.18	0.043
6	23.02.2022	3.4122	982.571	138.42	0.141
7	24.02.2022	8.6184	2496.292	124.83	0.050
8	25.02.2022	7.0500	2071.587	124.55	0.060
9	28.02.2022	9.6289	2193.880	106.45	0.049
10	02.03.2022	10.3648	2324.406	110.55	0.048
11	03.03.2022	10.5299	2348.132	95.02	0.040
12	07.03.2022	7.8736	1669.282	105.57	0.063
13	08.03.2022	9.7107	2022.193	92.64	0.046
14	09.03.2022	11.6303	2646.082	112.62	0.043
15	11.03.2022	10.1807	2289.453	100.61	0.044
16	15.03.2022	10.2188	2228.978	105.68	0.047
17	16.03.2022	12.6611	2857.928	100.1	0.035
18	17.03.2022	10.6059	2404.323	97.79	0.041
19	18.03.2022	10.8716	2441.713	101.08	0.041
20	21.03.2022	10.4274	2321.299	96.22	0.041
21	22.03.2022	10.0484	2243.759	112.16	0.050
22	23.03.2022	10.6421	2406.034	103.77	0.043
23	24.03.2022	13.0821	2981.571	94.05	0.032
24	25.03.2022	10.7011	2389.165	103.64	0.043
25	29.03.2022	11.7254	2676.303	107.73	0.040

where:
Q_j - fuel consumption, l;
A_j - performed transport work, pass·km;
j - workday number.

The hyperbola and exponential functions were chosen for approximation and reduced to a linear form by equivalent transformations. The approximation was performed using the least squares method.

As a result of the approximation, analytical dependencies are obtained:

$$Q_{p1} = \frac{0.457}{H_{avg}} - 0.00075 \quad (8)$$

$$Q_{p2} = 0.1669 \cdot e^{-0.1286 \cdot H_{avg}} \quad (9)$$

The sum of the squares of deviations of the model values, Q_{p1} and Q_{p2}, from the statistical data, is S_1=0.0004452 and S_2= 0.0014413, respectively. Based on that, the hyperbola function was chosen for further calculations (Figure 16).

The standard deviation of the model values from the experimental ones is $\bar{\sigma} = 0.0000178$. The relative standard deviation is $\bar{S}_r = 0.57\%$. As can be seen in Figure 16, the value of the specific fuel consumption Q_{p1} increases markedly with reduction of H_{avg} passenger traffic capacity to 20 passengers and below.

To validate the model obtained, the daily fuel consumption of Q_{calc} was calculated for three days of the observation period.

$$Q_{calc} = \sum_{i=1}^{n} Q_i \quad (10)$$

where:
n - the number of hauls the bus traveled during the working day.

The deviation errors of the calculated values from the statistical ones are determined (Table 7).

Based on the testing results, it can be stated that the model is quite adequate. The relative error δ of the calculated values does not exceed 10%. The magnitude of the simulation error is influenced, on the one hand, by the scattering of Q_{stat} fuel consumption statistics on individual days and, on the other hand, by the distance of technical mileage of the bus without passengers and its modes of movement in these sections.

The dependence obtained in Equation (8) allows to estimate the current values of fuel consumption of the bus on individual hauls, as well as on the section of the city route. Using this dependence, the current and total fuel consumption on the section of the route studied under the traffic conditions shown in Figure 11 were simulated for the time intervals of 6:30 and 9:30. The values obtained for the current and total fuel consumption of the bus on the route from the initial to the final stop are shown in Figure 17.

Fuel consumption is shown to be in the range of 0.081-0.477 l. The total fuel consumption in the study area is 7.257 l. The high fuel consumption in the 2nd and 13th hauls (Q_2=0.48 l, Q_{13} = 0.38 l) is explained by their length S_2 = 1.06 km and S_{13} = 0.86 km, respectively, which are the largest among other hauls on the route. Therefore, the current fuel consumption depends both on the passenger load of the bus and the length of the haul.

6 Discussion of research results and conclusions

Based on global priorities of energy savings and environmental safety, the management of modern urban passenger transport systems should focus on efficient use of passenger transport. Thus, there are issues of increasing the productivity of vehicles, reducing energy consumption and, therefore, reducing emissions of pollutants into the atmosphere. Research on this issue has shown that the solution of relevant problems is impossible without monitoring and evaluating the vehicle performance, such as speed, acceleration

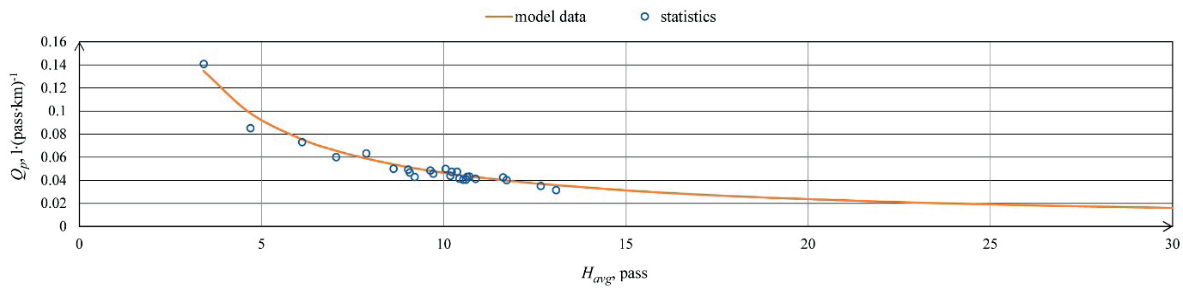


Figure 16 *Approximation of values of the bus specific fuel consumptions Q_p by hyperbola*

Table 7 *The results of the model testing*

Date	H_{avg}, pass	Q_p, l·(pass·km)$^{-1}$	Q_{calc}, l	Q_{stat}, l	Absolute error Δ, l	Relative error δ, %
23.02.2022	3.412	0.133178908	130.858	138.42	7.562	5.46
07.03.2022	7.8736	0.057293419	95.639	105.57	9.931	9.41
11.03.2022	10.181	0.044140827	101.058	100.61	0.448	0.45

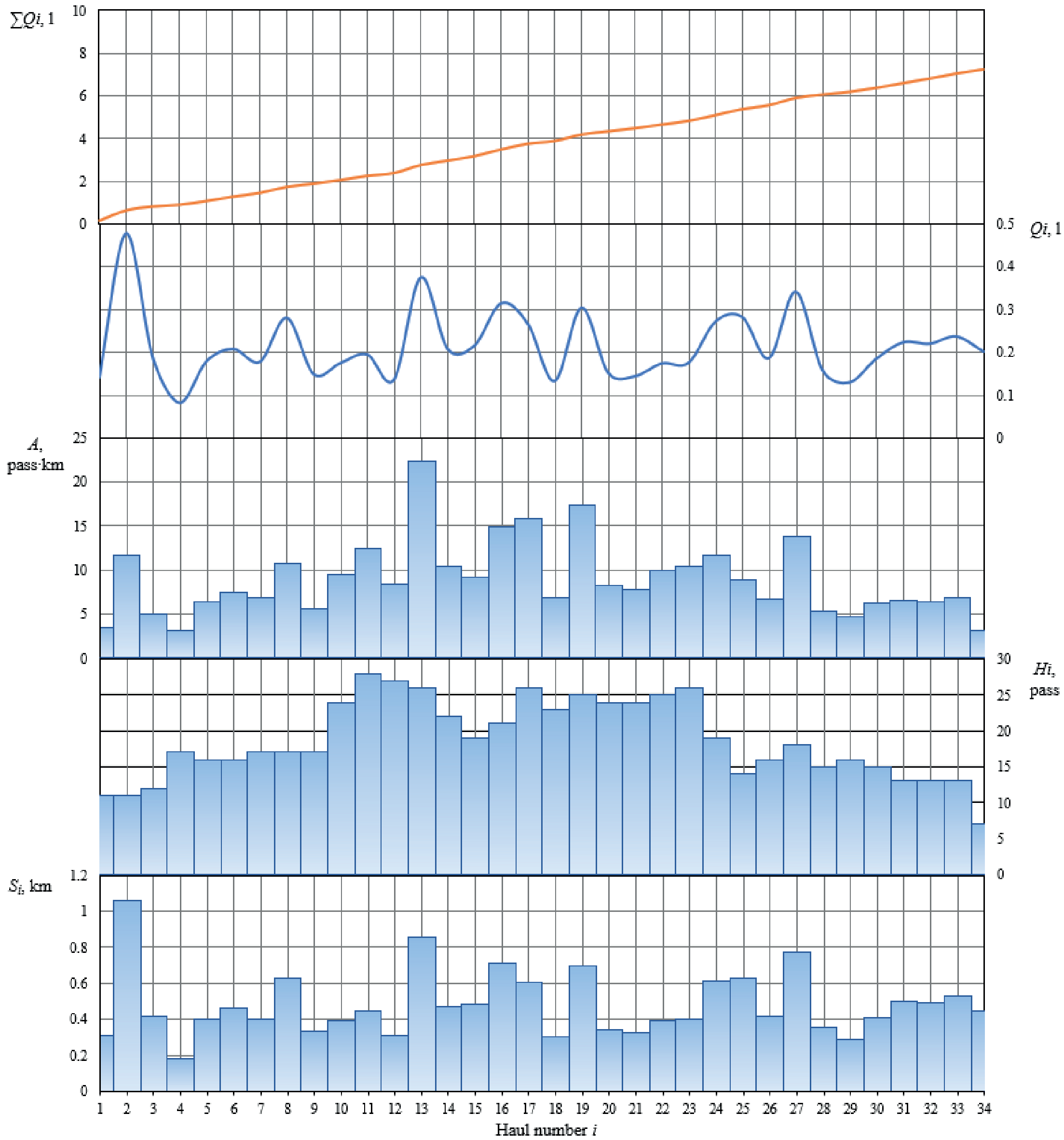


Figure 17 *Simulated bus fuel consumption in the individual hauls of the route*

in different modes of movement, fuel consumption, considering the distance passed and passenger flow parameters that change during the day.

As a part of the study, these indicators were measured on the bus route #13 in the city of Rzeszow with 35 stops in the direct and 38 stops in the back direction. The observation was carried out in 25 working days. The scientific substantiation of the volumes of the corresponding experimental samples is given. Statistical analysis of 70705 speed and acceleration values revealed that the average speed of the bus is 23.31 km·h^{-1} and the average speed on the route, considering the time of stops at bus stops and delays in traffic flow is 14.14 km·h^{-1}. The constructed distribution of the movement acceleration indicates that the main part of its values is in the range [-1,1] m·s^{-2}. The approximation of this distribution to the normal one is proved, which simplifies the further estimation of the general population parameters, according to the estimates of the sample statistics. The ranges and average values of speed and acceleration correspond to similar indicators of a large class of city buses in operation [13].

An analysis of the passenger traffic dynamics during the day was performed for a typical working day, which is selected by the volume of passenger traffic belonging to the class interval [650, 750] passengers per day with the highest distribution frequency of 40%. The working day was divided into six typical time intervals. The nature of changes in passenger traffic capacity in a fixed sequence of courses at different times of the day is shown to be similar and repeats the dynamics of total daily capacity in these hauls. Therefore, the time interval from 6:30 to 9:30 in the morning peak was considered to estimate the fluctuations in fuel consumption in individual hauls.

Analytical dependencies of fuel consumption on the number of passengers transported and the transport work performed per 100 km are built. The results of the obtained dependencies correlation analysis indicate insufficient correlation between these parameters of the system, that is, the inability to assess the nature of the Stat direct impact of transport work parameters on the absolute indicators of energy consumption. Based on this, it is proposed to estimate the energy consumption indirectly, through the specific fuel consumption per 1 passenger-kilometer. Approximation of experimental data is performed and the mathematical models are obtained that express the dependence of specific costs on the average daily power of the passenger traffic on the route. Among the approximating functions, the hyperbolic one is chosen, which gives the smallest sum of squares of deviations of the model values of specific costs from the experimental ones. In this case, the relative standard deviation is 0.57 %. Dependence analysis shows that the specific fuel consumption increases significantly (up to 8 %) when passenger load decreases below 15, increases significantly (more than 15 %) with less than 10 passengers and increases rapidly (more than 37 %) when passenger load decreases below 5.

The built model provides an opportunity to accurately determine the specific fuel consumption per passenger kilometer and, based on those, to calculate the absolute values of fuel consumption in individual hauls and sections of the route. The results obtained make it possible to determine the fuel consumption q per 100 km. The average value of q is 43.9 $l \cdot (100\ km)^{-1}$ and the most probable - 43.9 $l \cdot (100\ km)^{-1}$. The specified data confirm the results obtained in the work [13], where the average value of q, under the similar operating conditions, is equal to 43.2 $l \cdot (100\ km)^{-1}$. During the peak hours q reaches higher values than during the normal hours and is in the range 43.61-45.18 $l \cdot (100\ km)^{-1}$. Each city is characterized by its own specificity and traffic intensity, thus direct comparison of public bus fuel consumption is impossible. However, the scope of changes in fuel consumption influenced by the number of passengers is similar to that in the works [10, 21].

The model was evaluated according to the three days of the observation period. The days were chosen in such a way as to cover the ranges of average daily passenger traffic capacity: low, medium and high. The accuracy of the daily fuel consumption is in the 90.59-99.55 % interval. The relative error of the estimated daily values of fuel consumption does not exceed 10 %, which indicates a sufficient adequacy of the dependence. The magnitude of the simulation error is influenced, on one hand by the scattering of the statistical data on fuel consumption on certain days and, on the other hand, by the distance of technical mileage of the bus without passengers and its modes of movement in these sections.

The model was implemented in separate hauls of the transport network in the section of the studied bus route in the morning from 6:30 to 9:30. The estimated fuel consumptions on the hauls are in the range of 0.08 to 0.48 l and the total fuel consumption on the section of the route is 7.26 l. The high fuel consumption in the 2nd and 13th hauls (Q_2 = 0.48 l, Q_{13} = 0.38 l) is due to their maximum length S_2 = 1.06 km and S_{13} = 0.86 km, respectively, which are the largest among the hauls on the route. Therefore, the current fuel consumption depends both on the load of the bus and the length of the hauls.

Further research will be aimed at the energy efficiency of passenger vehicles taking into account driving modes, actual speed and acceleration on individual hauls and sections of the city route, driving style, as well as comparing the obtained results with the data of on-board means of fixing parameters. The influence of passenger load during the hauls on other characteristics of passenger transport, including fuel consumption in liters per 100 km, will also be investigated.

In addition, the obtained results will become the basis for development of new models and methods for determining other partial assessments of technical, economic and environmental efficiency as a part of a complex indicator of the transport systems functioning efficiency at different levels of detail.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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