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Study of the impact of route parameters on fuel consumption by buses in urban conditions

The work is devoted to improving the efficiency of passenger transport by studying the impact of route parameters on bus fuel consumption in urban conditions. Bus fuel consumption is a major component of transport costs and has a significant impact on fare setting, so the results obtained also have economic and social implications. It was found that one of the main technological indicators affecting bus fuel consumption is the number of stops on the route, since during acceleration and braking, more than 50% of fuel is spent on overcoming inertia. Based on the fuel balance equation, a mathematical model was developed to investigate the impact of the number of stops on bus fuel consumption, taking into account the number of passengers in the cabin. The results of the modelling (using the example of a typical city bus route in Dnipro) allowed us to draw conclusions about the nature of the impact of the number of stops per 1 km of route and the average length of the journey on bus fuel consumption. An empirical relationship was also obtained, which allows establishing a correlation between these parameters and information about the basic linear fuel consumption rate of vehicles. The presented results also allow assessing the technological and economic benefits of introducing more efficient bus modes of operation (e.g., express) in urban conditions.

Keywords: *bus route, fuel consumption, transportation cost, mathematical model, fuel balance, stop, speed of connection, traffic mode*

Introduction. In modern conditions, most cities in Ukraine are experiencing significant problems related to the growth of transport costs for the population due to the unbalanced development of transport systems and their inconsistency with the existing needs of the urban community and the economy. In this regard, the urgent tasks of sustainable urban development include improving transport planning methods and technologies [1].

One effective way to increase the efficiency of passenger transport is to organise more productive traffic modes on urban bus routes, such as express modes. Implementing such a measure reduces the time passengers spend travelling, increases bus utilisation and the level of transport service to the population without increasing the number of buses. Since express buses make fewer stops along the route, they brake and accelerate less, which significantly reduces fuel and lubricant costs, routine repairs and maintenance, and also reduces harmful emissions into the city's atmosphere [2-3]. Despite these advantages, express bus service has not been widely adopted on bus routes in Dnipro and most other cities in Ukraine, unlike in European Union countries [4-6].

Fuel costs are the main component of the cost of urban passenger transport. Currently, the Ministry of Infrastructure of Ukraine recommends calculating bus fuel consumption using a method based on information about the basic linear fuel consumption rate of a vehicle and a number of adjustment factors.

This approach does not fully take into account the possible operating modes of vehicles on the route, nor does it allow for an assessment of the economic benefits of introducing an express bus service from the point of view of fuel efficiency. This problem can be solved by creating mathematical models that take into account the operational fuel costs of buses under real operating conditions on city bus routes.

Analysis recent research and problem statement. Existing methods for determining vehicle fuel consumption are divided into the following groups: experimental; computational-statistical; analytical. The experimental method allows determining the fuel consumption rate for a specific vehicle in accordance with certain operating conditions. It requires lengthy testing and measurements, the results of which are used to obtain empirical correction coefficients [7]. It is labour-intensive due to the need to take measurements on different routes. The experimental method is only effective for determining individual route norms.

When using the calculation-statistical method, fuel consumption rates are established based on an analysis of statistical data on actual specific fuel consumption, as well as factors affecting changes in normal operating conditions. Multiple regression models are used as the mathematical apparatus. In practice, this method is widely used, but the need to simultaneously take into account several different operating factors significantly limits its use. The calculation-statistical method is convenient for developing group fuel consumption standards.

In modern conditions, the most advanced method is the analytical method using mathematical (or simulation) models of vehicle movement on individual sections of the route. It provides quick results and involves determining fuel consumption by calculation based on individual components of the transport process and operating conditions [8]. The accuracy of the method depends on the completeness of the model, which takes into account road, transport and climatic conditions. Despite the fact that the developed models require experimental verification, it is analytical methods that are necessary for practical use by ATP employees due to the absence of the need for lengthy and laborious experiments. Over the past decade, numerous works by such domestic scientists as Bodnar M.F. [9], Volkov V.P. [10], Gorbunov A.P. [11], Grubel M.G. [12], Dembitsky V.M. [13], Demyanuk V.A. [14], Kravchenko O.P. [15], Krivoshapov S.I. [16], Melnichuk C.V. [17], Rudzinsky V.V. [18], Sakhno V.P. [8], Firsov O.D. [19], Fornalchik E.Yu. [7], Chuiko S.P. [20], Yakunin M.E. [21] and others. However, the influence of bus movement mode on fuel consumption was not considered.

An analysis of studies [7-21] also showed that the fuel consumption of city buses is determined by a number of factors related to design, technology, operation, organisation, and natural and climatic conditions. According to the authors, one of the main indicators affecting bus fuel consumption is the number of stops on the route, because during acceleration and braking, more than 50% of fuel is spent on overcoming inertia.

The purpose and tasks of the study. The aim of this work is to study the influence of route parameters (primarily the number of stops) on bus fuel consumption in urban conditions using a mathematical model based on the vehicle fuel balance equation.

Materials and methods of research. The main indicator of energy efficiency for urban bus transport in most countries around the world is fuel consumption in litres per 100 km travelled (fuel consumption), which is determined on the basis of bench and road tests, or according to the following analytical relationship [8]:

$$Q_s = \frac{g_e \cdot N_e}{36 \cdot v \cdot \rho}, \tag{1}$$

where g_e – specific fuel consumption of the engine, g/(kW·h);

N_e – power developed by the engine in steady-state driving mode;

v – vehicle speed, m/s;

ρ – fuel density (the density of diesel fuel is 860 kg/ m^3).

When fuel burns in the engine cylinders, gas pressure builds up p_i, which, when it hits the pistons, creates indicator torque M_i, the value of which is directly proportional to the average gas pressure in the engine cylinders and its working volume $i \cdot V_h$. The indicator torque is spent on overcoming all types of losses in the car: mechanical losses in the engine P_M (friction of the pistons against the cylinder walls, pump drives and gas distribution system, etc.); losses in the drive of auxiliary equipment P_τ (fan, compressor, generator, etc.); losses in the transmission P_T; tyre rolling resistance P_f; aerodynamic drag P_w. The remaining part M_i is the reserve of traction that can be used to overcome inclines P_α and inertial forces P_j. The above indicators, applied to the wheels of the bus, form its power balance [10]:

$$\frac{p_i \cdot i \cdot V_h}{4\pi} \cdot \frac{U_T}{r_w} = P_M + P_\tau + P_T + P_f + P_w + P_j + P_\alpha , \tag{2}$$

where i – number of cylinders;
V_h – working volume of one cylinder, m^3;
U_T – transmission ratio;
r_w – wheel rolling radius, m;
$P_M + P_\tau + P_T + P_f + P_w + P_j + P_\alpha = P_i$ – sum of forces resisting the movement of the vehicle, which is transferred to its wheels, N.

Fuel consumption at a constant speed is determined by the following formula:

$$Q_s = \frac{g_{is}}{\rho} \cdot \left(P_M + P_\tau + P_T + P_f + P_w + P_j + P_\alpha\right), \tag{3}$$

where g_{is} – current specific fuel consumption (SFC) value (g/N·100 km).

Introducing the value P_M into the power balance of the bus simplifies the calculation of fuel consumption when driving in different gears, as well as its acceleration during engine braking. Based on (3), it is possible to construct a fuel balance for the bus, which can be used to study the mechanism of fuel consumption changes depending on the driving mode on the route. The calculated dependencies of the components of equations (2-3) are presented in [22].

The developed model was tested on city bus routes in Dnipro. During the simulation, the dynamic change in the additional mass of passengers (based on a survey of passenger flows) in the bus interior during route segments (4) was taken into account:

$$G_{j,j+1} = G + H_{j,j+1} \cdot m_p . \tag{4}$$

where $G_{j,j+1}$ – total weight of the bus between $j, j+1$ stops on the route, kg;
G – unladen weight of the bus, kg;
$H_{j,j+1}$ – bus occupancy between $j, j+1$ stops on the route;
m_p – conditional weight of one passenger ($m_n = 68$ kg).

Additional stops at traffic lights were determined using Bernoulli's distribution [23]:

$$P_u(e) = C_u^e \cdot p^e \cdot q^{u-e} = \left(\frac{u!}{e! \cdot (u-e)!} \right) \cdot p^e \cdot q^{u-e}, \tag{4}$$

where u – number of traffic lights on the route;
e – number of bus delays;
p – probability of free passage through a traffic light;
q – probability of delay at a traffic light.

The weighted average number of bus delays at traffic lights $M(e)$ when travelling along the route was determined according to the following relationship:

$$M(e) = \sum_{e \in u} e \cdot P_u(e). \tag{5}$$

Bus delay times at traffic lights were modelled based on the average duration of red and yellow signal phases according to a normal distribution.

When surveying passenger flows on route No. 34, which is operated by Bogdan A09204 buses running in route taxi mode, the number of bus stops during a trip varied from 20 to 58. Mathematical modelling of the transport process was performed for the following number of stops: 45 and 67 stops, corresponding to the conditions of bus operation in route taxi mode; 26 stops – operation of buses in normal (fixed) mode; and 14, 8 and 4 stops – operation of buses in express mode. The simulation results are presented in Table 1 and Fig. 1.

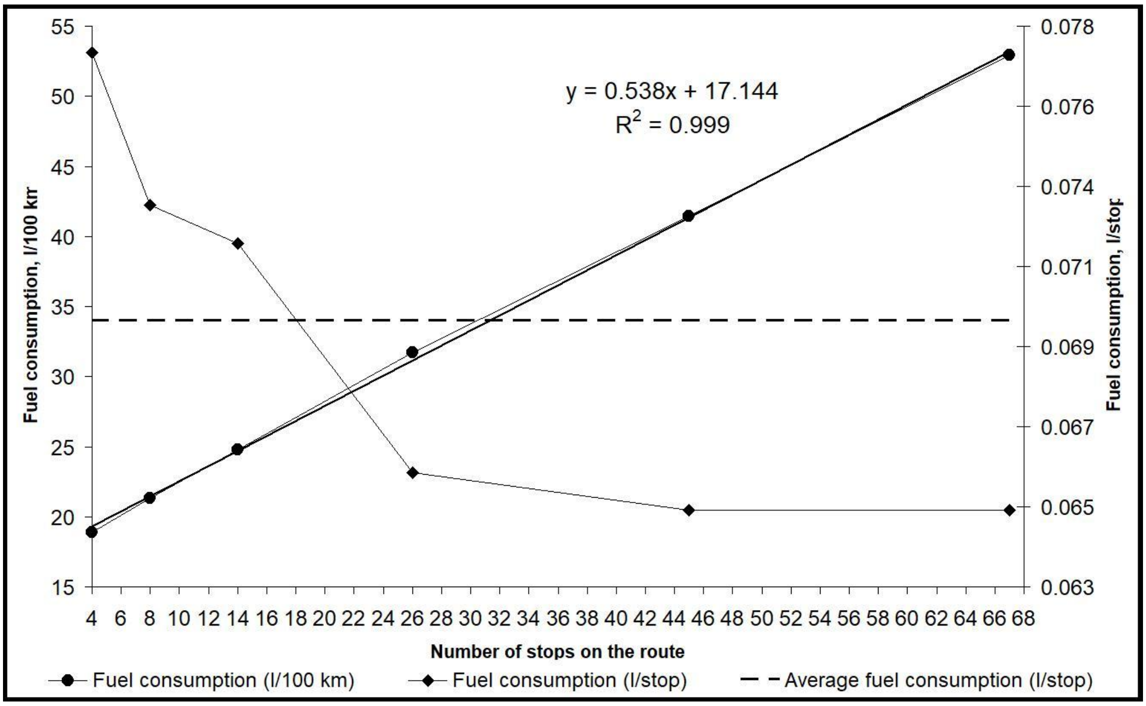

Fig.1. **Fuel consumption of Bogdan A09204 buses depending on the number of stops on route No. 34**

The simulation results show that fuel consumption on route No. 34 varies from 18.91 l/100 km (at $n_{stop} = 4$) to 52.95 l/100 km (at $n_{stop} = 67$), and the effect of the number of stops on fuel consumption in l/100 km is linear and can be approximated by equation (6) with a confidence level of R^2 =0.999 (Fig. 1):

$$Q^{Bogdan\ \ A09204}_{l/100\ \ km} = 17.144 + 0.538 \cdot n_{stop} \ . \tag{6}$$

Table 1. **Results of modelling bus traffic patterns on route No. 34**

Indicator	Bus service mode					
	Route taxi		Regular	Express		
Route length, km	12.7					
Number of stops on the route	67	45	26	14	8	4
Average length of a run, km	0.19	0.29	0.51	0.98	1.81	4.23
Number of stops per 1 km of the route	5.3	3.5	2.0	1.1	0.6	0.3
Flight duration, min.	38.13	32.75	28.05	25.05	23.38	21.67
Service speed, km/h	20.0	23.3	27.2	30.4	32.6	35.2
Operating speed, km/h	14.3	16.0	17.7	19.0	19.9	20.8
Fuel consumed during the flight, l	6.724	5.263	4.025	3.149	2.710	2.402
Average parameter values						
Fuel consumption, l/100 km	52.95	41.44	31.69	24.79	21.34	18.91
Effective power, hp	40.4	35.5	30.3	24.9	21.8	19.9
Cylinder pressure, MPa	0.58	0.55	0.51	0.47	0.45	0.44
Engine speed, rpm	1296	1311	1345	1375	1398	1439
Engine speed, rpm/km	3561	3046	2628	2360	2217	2088
Indicated efficiency, %	43.7	44.3	45.1	45.9	46.4	47.0
Positive torque on half-shafts, kN·m	3.04	2.32	1.6	1.04	0.73	0.53
Negative torque on half-shafts, kN·m	-0.21	-0.18	-0.16	-0.16	-0.15	-0.15
Power consumed for braking, kW	16.05	12.74	9.29	5.81	3.80	1.82
Number of gear changes	403	298	199	132	96	72
Ratio of total transmission time to total operating time, %						
Neutral	36.2	31.2	24.1	17.7	13.2	6.8
1st gear	7.4	5.8	3.9	2.3	1.3	0.6
2nd gear	4.6	3.6	2.5	1.5	0.9	0.4
3rd gear	10.5	8.2	5.5	3.3	1.9	0.9
4th gear	12.6	9.6	6.4	3.8	2.2	1.1
5th gear	9.0	5.3	3.7	2.2	1.3	0.6
6th gear	19.7	36.3	53.9	69.2	79.2	89.6
Ratio of total distance travelled in gear to total distance travelled, %						
Neutral	13.4	9.4	5.6	2.9	1.4	0.8
1st gear	1.6	1.1	0.6	0.3	0.2	0.1
2nd gear	2.8	1.9	1.1	0.6	0.3	0.1
3rd gear	11.1	7.3	4.2	2.2	1.2	0.5
4th gear	19.5	12.7	7.3	3.8	2.1	0.9
5th gear	15.6	8.5	5.2	2.7	1.5	0.6
6th gear	36.0	59.1	76.0	87.5	93.3	97.0
Components of fuel balance consumption, %						
Aerodynamic drag	2.8	4.3	6.7	9.9	12.6	15.6
Tyre rolling resistance	6.3	8.3	11.2	15.4	19.2	22.7
Transmission resistance	1.8	2.1	2.6	3.3	3.8	4.4
Mechanical resistance in the engine	18.8	21.2	25.1	30.8	35.7	40.5
Road gradient resistance	3.8	3.9	4.1	4.2	4.3	4.3
Resistance to overcoming inertia	66.5	60.2	50.3	36.4	24.4	12.5

The nature of the linear influence of the number of additional stops on vehicle fuel consumption is explained in [24]: "... vehicle fuel consumption consists of the costs of acceleration – Q_a, braking – Q_b, idling – Q_i and driving at a constant speed – Q_v.

$$Q = Q_a + Q_b + Q_i + Q_v \text{ or } Q = Q_v + q_{stop} \cdot n_{stop}, \tag{7}$$

where q_{stop} – additional fuel consumption per stop, litres/stop.

Work [24] also presents the results of experimental studies to determine q_{stop} for vehicles with diesel engines whose working volume and power are similar to those of the Bogdan A09204 bus engine. They range from 0.06 l to 0.10 l per stop (depending on the final acceleration speed from 40 to 60 km/h), with an average of 0.078 l. Fig. 1 shows the calculated values q_{stop} obtained for the Bogdan A09204 bus, which vary from 0.063 litres (at $n_{stop} = 67$) to 0.077 litres (at $n_{stop} = 4$), with an average value of 0.070 litres. The insignificant variation (within 10%) in the values $q_{зуп}$ is explained by the difference in the final acceleration speeds of buses on sections of different lengths and coincides with the results of studies presented in [24].

Currently, the Ministry of Infrastructure of Ukraine recommends calculating fuel and lubricant consumption (FLC) for buses using method [25], which is based on information about the basic linear fuel consumption rate for the vehicle H_{BLN} and a number of correction factors (8). According to [25], the basic linear fuel consumption rate for Bogdan A09204 buses is H_{BLN} =16.1 l/100 km; the correction factors that take into account operation in urban conditions K_T =15%; operation that requires frequent stops K_S =10%; and the age of the bus K_E =9%. Thus, the standard operating fuel consumption of Bogdan A09204 buses when operating on urban routes is:

$$\begin{gathered} Q_{FUEL} = 0{,}01 \cdot H_{BLN} \cdot S \cdot \left(1 + 0{,}01 \cdot \left[K_T + K_S + K_E\right]\right) \\ Q_{FUEL} = 0.01 \cdot 16.1 \cdot 100 \cdot \left(1 + 0.01 \cdot \left[15 + 10 + 9\right]\right) = 21.6 \text{ l/100 km.} \end{gathered} \tag{8}$$

Fig. 2 shows a joint analysis of the standard operating fuel consumption for Bogdan A09204 buses and the fuel consumption obtained from the simulation results.

Analysis of the information presented in Fig. 2 shows that the fuel consumption of buses operating in normal mode ($n_{stop} = 26$, $\overline{l_{SPAN}} = 0.51$ km) exceeds the standard values by 36%; and in route taxi mode ($n_{stop} = 46$, $\overline{l_{SPAN}} = 0.28$ km) by 86%. This fact can be explained, firstly, by the fuel balance structure of the Bogdan A09204 bus (Fig. 3), in which the costs of overcoming inertia forces when stopping account for more than 50%. Secondly, it is due to the distribution of the ratio of the total operating time in gear to the total engine operating time (Fig. 4), which shows that the operation of buses in normal mode and in route taxi mode involves prolonged driving in 1st to 4th gears (from 18.3 to 35.1%), which consume significantly more fuel than when driving in the higher 5th or 6th gears.

Thus, the introduction of express mode on the route will reduce fuel consumption by 30% thanks to a reduction in additional fuel costs, which are equal to $q_{stop} \cdot n_{stop}$ and a reduction in the duration of driving in 1st to 4th gear.

To test the resulting model (6), experimental studies were conducted (after each trip, when passenger traffic was surveyed, the bus tank was filled to capacity) on fuel consumption on route No. 34, which are marked in Fig. 2 with the symbol ▲. The results obtained show sufficient correspondence between the calculated and experimental values and have a spread of values within 10%.

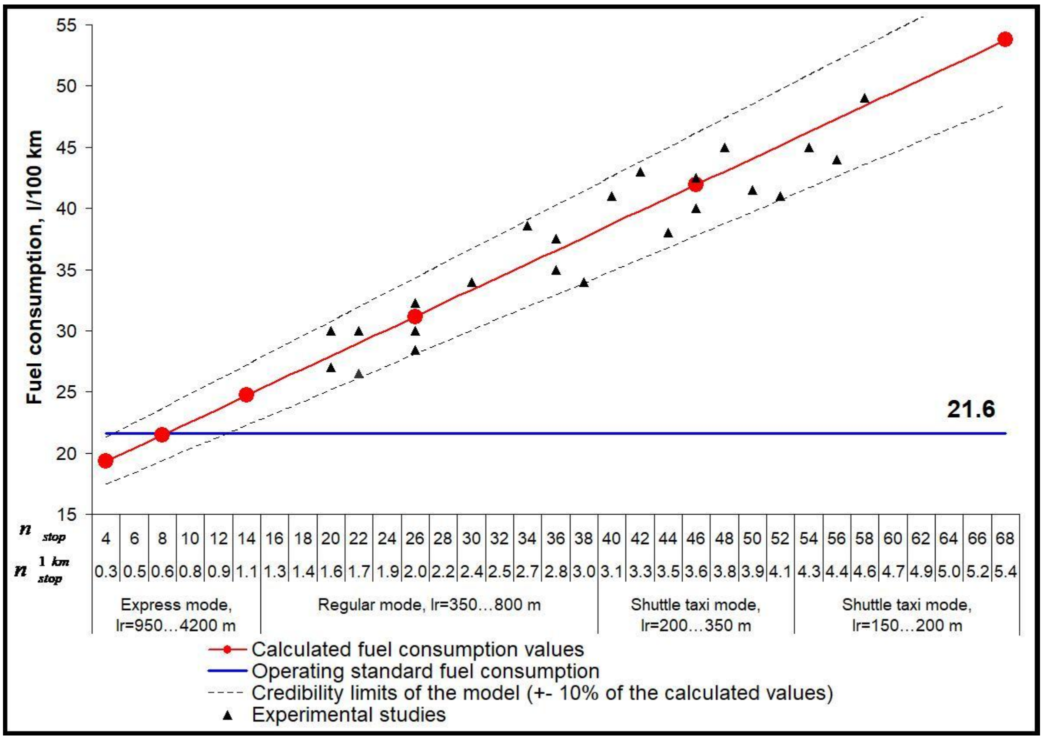

Fig. 2. **Joint analysis of operational fuel consumption standards for Bogdan A09204 buses and fuel consumption obtained from modelling results**

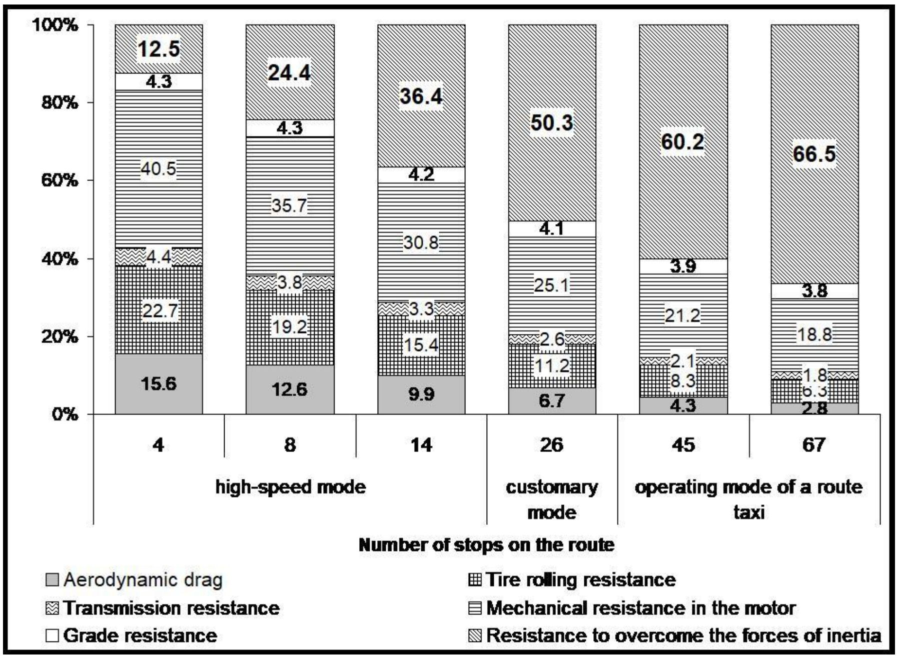

Fig. 3. **Fuel balance structure of the Bogdan A09204 bus**

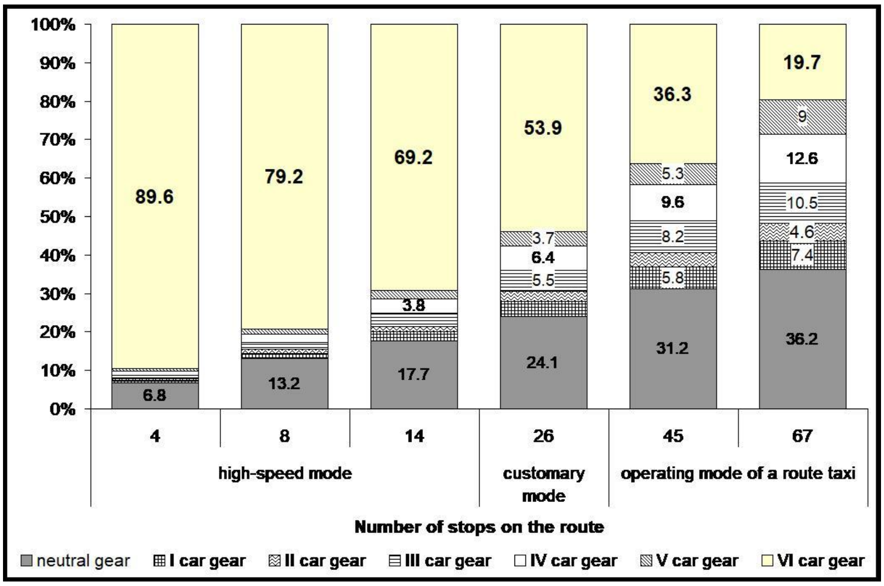

Fig. 4. **Distribution of the ratio of total operating time in i-th gear to the total operating time of the Bogdan A09204 bus engine**

It should be noted that the dependence of fuel consumption of Bogdan A09204 buses on the number of stops on route No. 34 (6), $Q^{Bogdan\ A09204}_{l/100\ \ km} = 17{,}144 + 0{,}538 \cdot n_{stop}$ obtained as a result of modelling, is specific in nature and therefore cannot be used for other routes. Thus, dependence (6) needs to be converted to a form that excludes the link to the length of route No. 34. The number of vehicle stops per 1 km of mileage was chosen as such a generalised indicator:

$$n^{1km}_{stop} = \frac{n_{stop}}{L_R}\,. \tag{9}$$

The dependence of bus fuel consumption as a function of n^{1km}_{stop} was obtained based on the information presented in Fig. 2 and is as follows:

$$Q^{Bogdan\ A09204}_{l/100\ \ km} = 17.144 + 6.835 \cdot n^{1km}_{stop}\,. \tag{10}$$

Given the relationship between n^{1km}_{stop} and the average length of the route $\overline{l_{SPAN}}$, it is advisable to present expression (10) in a form that is convenient for assessing the energy efficiency of transport on any route when using different bus operating modes:

$$Q^{Bogdan\ A09204}_{l/100\ \ km} = 17.144 + 6.835 \cdot \left(\frac{L_R + \overline{l_{SPAN}}}{L_R \cdot \overline{l_{SPAN}}} \right). \tag{11}$$

The reliability of the model obtained (11) is confirmed by the results of studies presented in [26]. According to the results of calculations (which were performed using the method [8]), it was established that the fuel consumption of Bogdan A09204 buses in the urban driving cycle is 29.2 l/100 km. The distribution of stops in a standardised urban driving cycle, according to State Standard 20306, corresponds to the average length of a route $\overline{l_{SPAN}}$ =550 m, for which the fuel consumption according to the obtained dependence (11) is 29.9 l/100 km (Fig. 5).

The introduction of an express mode on the route also allows for an increase in bus speed on the route by more than 30% (Table 1, Fig. 5) and, accordingly, their productivity by reducing the duration of the trip. Analysis of the simulation results on other routes where different bus models are operated has established a relationship between the coefficients of models (10) and (11) and the basic linear fuel consumption rate (H_{BLN}):

$$Q_{l/100\ \ km} = H_{BLN} \cdot \left[1.065 + 0.425 \cdot n_{stop}^{1km}\right];$$

$$Q_{l/100\ \ km} = H_{BLN} \cdot \left[1.065 + 0.425 \cdot \left(\frac{L_R + \overline{l_{SPAN}}}{L_R \cdot \overline{l_{SPAN}}}\right)\right]. \qquad (12)$$

Thus, the established empirical relationships (12) allow for the assessment of the energy efficiency of most bus models depending on the mode of operation on urban bus routes.

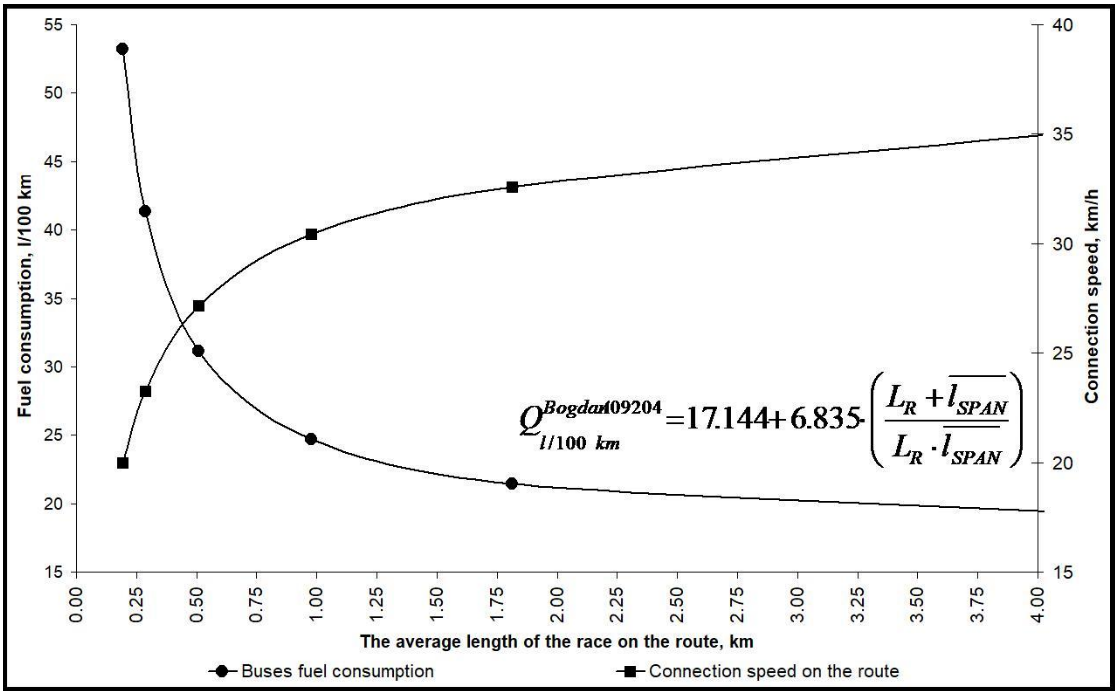

Fig. 5. **The impact of the average length of a route on bus fuel consumption and service speed**

Conclusion. Bus fuel consumption is a major component of transportation costs and significantly affects fare setting, so research related to reducing fuel consumption has economic and social implications. It has been established that one of the main technological indicators affecting bus fuel consumption is the number of stops on the route, since during acceleration and braking, more than 50% of fuel is spent on overcoming inertia.

Currently, the Ministry of Infrastructure of Ukraine recommends calculating fuel and lubricant consumption for buses using a method based on information about the basic linear fuel consumption rate for vehicles. This approach does not take into account all factors affecting fuel consumption by buses when operating in real conditions. It also does not allow carriers to assess the economic benefits of more progressive bus operating modes (e.g., express mode).

Based on the fuel balance equation, a mathematical model was developed that allows investigating the impact of the number of stops on bus fuel consumption, taking into account passenger occupancy.

The results of the modelling (using the example of city bus route No. 34 in Dnipro) allowed us to draw conclusions about the nature of the impact of the number of stops per 1 km of the route and the average length of the journey on bus fuel consumption. It was found that fuel consumption on route No. 34 varies from 18.91 l/100 km (at $n_{stop} = 4$) to 52.95 l/100 km (at $n_{stop} = 67$). In turn, the standard operating fuel consumption of Bogdan A09204 buses, in accordance with the methodology of the Ministry of Infrastructure of Ukraine, is 21.6 l/100 km. Thus, the fuel consumption of buses operating in normal mode ($n_{stop} = 26$, $\overline{l_{SPAN}} = 0{,}51$ km) exceeds the standard values by 36%; and in route taxi mode ($n_{stop} = 45$, $\overline{l_{SPAN}} = 0{,}29$ km) by 86%. Thus, the introduction of express mode on the route will reduce fuel consumption by 30% and increase the speed of service on the route by more than 25%. An empirical relationship was also obtained, which allows establishing a correlation between these parameters and information about the basic linear fuel consumption rate of vehicles.

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Дослідження впливу технологічних параметрів маршруту на витрати палива автобусів в міських умовах

Анотація. *Робота присвячена підвищенню ефективності пасажирських перевезень за рахунок дослідження впливу технологічних параметрів маршруту на витрати палива автобусів в міських умовах. Витрати палива автобусів є головною складовою у собівартості перевезень і значною мірою впливають на формування тарифу, тому отримані результати мають також економічний та соціальний ефект. Було встановлено, що одним з основних технологічних показників, які впливають на витрати палива автобусів, є кількість зупиночних пунктів на маршруті, оскільки під час розгону та гальмування понад 50% палива витрачається на подолання сил інерції. На підставі рівняння паливного балансу була розроблена математична модель, яка дозволяє дослідити вплив кількості зупиночних пунктів на витрати палива автобусів з урахуванням наповнення салону пасажирами. Результати проведеного моделювання (на прикладі типового міського автобусного маршруту у м. Дніпро) дозволили зробити висновок, щодо характеру впливу кількості зупинок на 1 км маршруту та середньої довжини перегону на витрати палива автобусів. Також була отримана емпірична залежність, яка дозволяє встановити взаємозв'язок між цим параметрами та відомостями про базову лінійну норму витрати палива транспортних засобів. Представлені результати також дозволяють оцінити технологічні та економічні переваги від впровадження більш продуктивних режимів руху автобусів (наприклад експресного) в міських умовах.*

Ключові слова: *автобусний маршрут, витрати палива, собівартість перевезень, математична модель, паливний баланс, зупиночний пункт, швидкість сполучення, режим руху.*