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EXPRESS BUS MODE AS AN ALTERNATIVE WAY OF IMPROVING THE ENVIRONMENTAL SAFETY OF CITIES

Purpose. To propose a modern methodological approach to determine the energy efficiency of passenger transportation by city buses by establishing the relationship between fuel consumption and the number of stops on the route, as well as an environmental assessment of the introduction of an express mode of bus traffic in the conditions of a modern metropolis.

Methodology. The fuel balance equation of the vehicle was used to build a model for researching the energy resource efficiency of buses in different driving modes. Determining the criteria and limitations that determine the effectiveness of the express mode of bus traffic was carried out by methods of system analysis. Information about the number of stops (where passenger exchange takes place) and additional dynamic loads which are related to the level of occupancy of the bus cabin were used as input data for modelling. These indicators were determined on the basis of a survey of passenger flows. The values of the angles of the lateral-longitudinal slope of the road and the distances of the sections between the stops were determined with the help of the Internet resources Google Earth Pro and Google maps, respectively. The number of additional stops at traffic lights was calculated as a weighted average value according to the Bernoulli distribution. Elements of functional analysis were used to justify the introduction of the combined mode of movement in the considered example. The economic evaluation was carried out in accordance with the Directive of the European Parliament and the Council of the EU 2009/33/EU.

Findings. In the conducted studies, an ecological and economic evaluation of the introduction of an express mode of bus traffic in the conditions of a modern metropolis was provided. The results of the conducted research made it possible to determine the dependence of the energy resource efficiency of bus operation in different driving modes. Increasing the energy efficiency of transportation is achieved through the introduction of more productive and less expensive modes of bus traffic on city routes. It has been proven that the most effective one is the combined mode using regular and express connections.

Originality. The authors believe that one of the effective measures to reduce the environmental consequences of the operation of urban public automobile transport is to increase the energy efficiency of transportation. This conclusion is based on the fact that one of the main quantitative indicators of the operation of vehicles is fuel consumption, which directly affects the mass of pollutant emissions and depends on the bus driving mode.

Practical value. The proposed methodological approach is a universal algorithm that is proposed to be used by interested parties to assess the possibilities of reducing the negative impact of transport on the environment. The use of the developed approach in practice allows transport departments of city halls and akimats of megacities together with specialists of transport companies (developers of public transport routes) to reduce emissions of pollutants into the atmospheric air, achieving a minimal negative impact on the environment.

Keywords: *transport service, driving mode, fuel efficiency, harmful emissions, environmental safety*

Introduction. A modern city is a complex, dynamic, developing system. A sufficient level of environmental safety of this system is provided by a number of subsystems: transport, health care, education, cultural and household services, recreation, landscaping, green spaces, street and road network, security, etc.

According to the World Health Organization, air pollution is one of the main environmental health risk factors. Therefore, the problem of increasing the level of environmental safety due to the factor of gasification has social, technical, ecological, and economic aspects. The presence of harmful substances in the air leads to an increase in the number of diseases and the severity of the course of such diseases as stroke, heart disease, lung cancer, acute and chronic respiratory diseases, including asthma. Thus, reducing the impact of air pollution on human health is important both for saving human lives and for reducing economic losses associated with premature deaths and illnesses of the working population of countries. One of the biggest sources of environmental pollution with atmospheric exhaust gases in cities is road transport (including public transport) [1]. The main factors of intensive air pollution by motor vehicles in megacities are the heavy traffic of the road and transport network, the operation of a technically outdated car fleet and the low quality of fuel and lubricants.

In order to obtain a complete, objective picture regarding the determination of the energy efficiency of passenger transportation by city buses, the authors conducted full-scale research at the modern theoretical and technological level using the methods of system analysis in selected cities of Ukraine and Kazakhstan – Dnipro and Almaty. Dnipro is one of the largest industrial, economic, and educational centres of Ukraine. Dnipro has an extensive route network, which as of October 1, 2023, consists of 92 bus routes to meet the needs of the city's residents in a high-quality and timely manner for work, education, and cultural and everyday travel. According to the report of the Department of Transport and Infrastructure of Dnipro in September 2023, the average number of buses on bus routes for one day was 695 units (of which 101 were large-capacity buses, 273 were medium-capacity buses, and 321 were minibuses).

Almaty, the largest metropolis of Kazakhstan, which operates 163 bus routes distributed among 24 carriers. According to the report of the transport department of the Almaty akimat in

September 2023, the average number of buses operating on the routes for one day was 1,695 units. The total fleet of the city with a reserve is 2,441 buses, of which 1,715 are diesel ones, 515 gas ones, 15 electric buses, and 196 trolleybuses.

Research in the field of fuel efficiency of vehicles has shown that the fuel consumption of city buses is influenced by many factors. The most significant of them are the factors that characterize the operating conditions of the rolling stock on the route (average speed of connection, plan and profile of the route, average length of the run, intensity of traffic flow, etc.). Much attention was paid to the study of these factors in various scientific works, since the average fuel consumption between routes can differ by 1.5–2 times. The research presented in this article is devoted to determining the impact of the number of bus stops on bus routes in the city of Dnipro on the fuel consumption of buses, using a mathematical model developed based on the fuel balance equation. Similar studies were conducted in the conditions of the city of Almaty. This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14872548 Modern environmental Law and order: Kazakhstan case). The verification of the obtained results for operational and technical factors in the conditions of the diverse surrounding landscape of the cities of Dnipro and Almaty will be presented in the next work.

Urban passenger road transport is extremely important for ensuring the social life and industrial activity of any modern city. In recent years, its specific weight in the total volume of transportation is about 45 %. But it is also one of the main sources of negative anthropogenic impact on the environment, especially air pollution. For example, one medium-capacity bus, running an average of 50,000 km per year, burns 12.5 tons of diesel fuel, for which it is necessary to process 20.8 tons of oil. About 187.5 tons of air (37.5 tons of oxygen) is used to burn this amount of fuel. Also, buses emit about 200 pollutants into the atmosphere together with exhaust and crankcase gases, which cause toxic, mutagenic, carcinogenic and other types of effects on living organisms [2], including: oxides and carbon dioxide (CO, CO_2); nitrogen oxides and dioxides (NO, NO_2); sulphur dioxin (SO_2); methane (CH_4); finely dispersed solid particles (FDSP), soot (SP); benz(a)pyrene ($C_{20}H_{12}$); non-methane volatile organic compounds (NMVOC), which include alcohols, aldehydes, alkanes, aromatic hydrocarbons, ketones and their halogenated derivatives; etc. The given facts testify to the need for systematic implementation of multi-faceted measures to increase environmental safety in the operation of road transport.

Literature review. The relevance of the problem of the negative impact of transport on the environment, as well as the need to develop measures to reduce the number of harmful emissions into the atmosphere, is of great interest to modern scientists all over the world. The main and most widespread method for increasing environmental safety is the reduction of harmful emissions from vehicles by their neutralization and capture. Therefore, many works are devoted to the study of emissions of automobile vehicles (AV).

An integrated methodology for estimating emissions based on the example of the fleet of the Madrid Municipal Transport Company is proposed in [3]. The results of modelling fuel consumption in urban conditions were confirmed by their comparison with actual consumption.

In the work by Zheng, et al. [4] modelling of bus emissions is carried out using smart maps. It was found that 10-30 km long routes account for 81 % of total emissions from buses, and the average level of emissions is 56.2 g CO_2/km. Bus emissions have cyclical fluctuations on holidays, weekdays, and weekends. The authors recommend fully electrifying the Beijing bus fleet, which will reduce emissions by 71 % compared to diesel buses.

Järvinen, et al. [5] performed a quantitative assessment of the emissions of city buses running on diesel fuel in the city of Helsinki (Finland) with the help of a mobile laboratory. EEV and Euro VI standard buses were compared. The average emission factors of particulate matter number (PN), particulate matter mass (PM and BC) of converted EEV buses were at the same level as Euro VI standard buses, but their PM emissions were significantly different. On average, EEV buses emitted the highest amount of nanocluster aerosol (i. e. particles between 1.3 and 3 nm in size). High NCA emissions were associated with high PN emissions. The results show that improved exhaust aftertreatment systems reduce emissions of larger soot particles, but do not always reduce emissions of fine particles.

In a study by Mahesh, et al. [6], a quantitative assessment was carried out of bus emissions during peak and off-peak periods of the day, based on the data of four bus routes operating in the city of Chennai in India. Data collected using GPS receivers. Second-day data on speed and acceleration were used to determine the mode of operation of buses. The obtained results showed an increase in total CO_2, CO, HC and NO_x emissions from the bus during peak periods compared to off-peak periods by 17, 16, 37 and 21 %, respectively.

An assessment of the impact of congestion on emissions from city buses in Madrid (Spain) is presented in the article by Rosero, et al. [7]. A comparison of two scenarios: free flow and severe congestion showed that the average speed of traffic on the route decreases by 50 % and the number of stops per kilometre increases by 1.5 times. At the same time, CO_2 and NO_x emissions from buses running on natural gas increased by 50 and 85 %, respectively. In turn, diesel buses demonstrated less sensitivity to fluctuations in the level of traffic jams.

The work by Giraldo, et al. [8] is dedicated to the study of fuel consumption and emissions of CO_2, CO and NO_x for diesel passenger buses in real operating conditions in high-altitude cities (>2,000 above sea level) and in mountainous regions with an average road gradient of 4 %. Average fuel consumption of 0.41 L/km and emissions of 965.8, 41.4 and 5.3 g/km for CO_2, CO and NO_x, respectively, were obtained for a city with high traffic intensity (Mexico City). Fuel consumption and CO_2 emissions were within expected values. However, CO emissions turned out to be three times higher, and NO_x emissions were 50 % of the values specified in the technical characteristics for buses of a similar design operating in low-lying areas.

The next large cluster of research is the works dedicated to the improvement of internal combustion engine (ICE) designs and their ability to work on alternative types of fuel, the use of new types of power plants and forward-looking transmissions.

In the article Kim, et al. [9] analysed the feasibility of using hydrogen diesel fuel for city buses in Seoul. A simulation of driving a vehicle equipped with a six-cylinder engine with a volume of 11,046 cm^3 shows an average fuel economy of 121.7 g/km. This confirms the efficiency of hydrogen-powered buses compared to buses that run on compressed natural gas.

In the work by Jelti, et al. [10], an ecological assessment is presented of the life cycle of hybrid, electric and hydrogen fuel cell buses in the conditions of the city of Oujda, Morocco. Total energy consumption by fuel type and greenhouse gas emissions were chosen as the main criteria. The authors found that electric and hydrogen fuel cell buses are an effective and sustainable alternative to public transport that runs on fossil fuels.

The purpose of the article by Rossetti, et al. [11] is a study of emission reductions of buses that are equipped with stepless hydromechanical transmission (SHT) in comparison with a manual transmission. For this purpose, a one-dimensional simulation model of a 12-ton city bus equipped with a Power-Split SHT was developed in the AMESim environment. The simulation results showed that SHT can reduce fuel consumption and emissions (compared to a traditional transmission) if operated according to appropriate control strategies. The effectiveness of using SHT to improve fuel efficiency and reduce emissions has also been repeatedly proven in works [12, 13].

Comprehensive approaches to improving the environmental indicators of the use of motor vehicles are considered in works [14–17]. Garcia, et al. [14] investigate ways to reduce

CO_2 emissions using the example of the 10 largest bus routes in the city of Valencia. For each route, the optimal level of hybridization was established, the sizes of batteries and electric motors were optimized. The growth potential of fuels produced from renewable sources was also assessed.

The work by Shao, et al. [15] investigates the problem of obtaining a balance during the formation of a mixed fleet of diesel and electric buses, under the condition of minimizing the total emissions of greenhouse gases and operating costs. The simulation was performed for the bus network of the city of Liuzhou in China. It was established that it is advisable to operate electric buses on bus routes that are located in the city centre with larger passages flow. And the majority of diesel buses must be assigned to long-distance routes located in the suburbs. The implementation of this measure will reduce carbon emissions from 207.15 to 47.56 tons per day.

Thus, the article by Kowarik [16] provides an overview that traces the development of the Berlin School of Urban Ecology over the past 50 years, summarizes its main approaches and results, demonstrates how they contributed to the planning of Berlin as a green, biodiverse city, as well as the development their contribution to urban ecology in an international perspective is assessed.

Projections of future energy consumption, greenhouse gas emissions, and pollutants by buses in representative Canadian cities are presented in Tian, et al. [17]. Under the scenario of high oil prices, this study took into account upfront costs for infrastructure, social costs from pollution, as well as the dynamics of carbon emission prices and fuel prices, which made it possible to conduct a comprehensive analysis of the costs of reducing carbon emissions under the time of the transition period. If the proposed measures are implemented, greenhouse gas emissions from bus transport in Toronto, Montreal, Edmonton and Halifax could be reduced by 18.7, 30.1, 21.3 and 34.6 %, respectively.

It is also impossible not to pay attention to works devoted to fuel consumption, for example [18, 19]. In the article Dreier, et al. [18] estimated fuel consumption and greenhouse gas emissions for six types of city buses with conventional and hybrid electric power plants used in the Bus Rapid Transit (BRT) system in Curitiba, Brazil. The simulations were performed on real driving models collected in Curitiba, comprising 42 driving cycles. The obtained results showed that hybrid-electric buses consume 30 % less fuel compared to ordinary city buses equipped with internal combustion engines.

The work by Prati, et al. [19] describes the results of research on the effect of cold engine start on the fuel consumption and emissions of city buses running on natural gas in three Italian cities under real driving conditions. It was established that a cold start strongly affected CO and NO_x emissions because of temperature on the efficiency of the catalytic converter, and excess emissions in the cold state strongly depend on the temperature of the surrounding environment and the coolant.

The assessment of the impact of vehicles running on biodiesel fuels on the biosphere was studied in [20].

Separately, we will highlight that the rational operation of means of transport is also in the field of view of researchers, but a limited number of works are devoted to it, among which we will highlight [11, 21, 22].

The article Foda, et al. [21] considers the problems associated with the operation of battery electric buses (BEBs) operating in transit mode. To solve them, a model for calculating BEB costs and greenhouse gas emissions was developed. It allows you to optimize the size and location of the charging infrastructure, the capacity of the on-board battery, as well as the vehicle charging schedule.

The work by Ghaffarpasand, et al. [22] is devoted to the study of the influence of vehicle management on emissions and fuel consumption of city buses. A comprehensive data collection was carried out on the main routes of the city, and then a bus driving cycle was developed using a random trip selection method. The dependences of the influence of bus speed and passenger flow on emissions and fuel consumption were established.

The authors believe that one of the effective measures to reduce the environmental consequences of the operation of urban public road transport is to increase the energy efficiency of transportation. This hypothesis is based on the fact that one of its main quantitative indicators of the operation of vehicles is fuel consumption, which directly affects the mass of pollutant emissions and depends on the bus driving mode.

Increasing the energy efficiency of transportation can primarily be implemented through the introduction of more productive and less costly modes of bus traffic on city routes. According to the Law of Ukraine "On Road Transport", the transportation of passengers on a public bus route can be carried out in three modes of traffic: regular (buses stop at all stop points (SP), which are provided for in the timetable), express (buses stop at some SPs, which are characterized by maximum passenger traffic); and in the route taxi mode (boarding and disembarking passengers takes place at the request of passengers where it is not prohibited by the Traffic Rules).

The simultaneous application of several bus traffic modes on one route forms a combined traffic mode. The most effective is the combined mode with the use of ordinary and express connection. It allows one to reduce the time spent by passengers on movement, to increase the degree of use of buses and the level of public transport service without increasing the number of buses. Since express buses have fewer stops on their way, they make less braking and accelerating, which contributes to a significant reduction in the cost of fuel and lubricants, which in turn reduces the amount of harmful emissions into the city atmosphere.

The analysis of literary sources showed that fuel consumption of city buses is determined by a number of structural, technological, operational, organizational and natural-climatic factors. According to the authors, the determining factors that characterize the efficiency of the express mode of bus traffic, in accordance with the fuel consumption of buses, are: the average length of the route (distance between two adjacent stops) and the frequency of unscheduled stops on the route, taking into account the filling of the bus cabin.

It was these factors that were used as model variables during the study of the influence of city bus traffic modes on the energy efficiency of transportation and the number of harmful emissions.

Purpose. The purpose of the work is to study the energy efficiency of city bus transportation by establishing the relationship between fuel consumption and the number of stops on the route, as well as an environmental assessment of the introduction of an express mode of bus traffic in the conditions of a metropolis.

Methods. The fuel balance equation of the vehicle was used to build a research model of the energy resource efficiency of buses in different driving modes. Determining the criteria and limitations that determine the effectiveness of the express mode of bus traffic was carried out by methods of system analysis. Information about the number of stops (where passenger exchange takes place) and additional dynamic loads, which are related to the level of occupancy of the bus cabin, were used as input data for modelling. These indicators were determined on the basis of a survey of passenger flows. The values of the angles of the longitudinal slope of the road and the distances of the sections between the stops were determined with the help of the Internet resources Google Earth Pro and Google maps, respectively. The number of additional stops at traffic lights was calculated as the weighted average value according to the Bernoulli distribution. Elements of functional analysis were used to substantiate the introduction of the combined mode of movement in the considered example. The economic evaluation was carried out in accordance with the Directive of the European Parliament and the Council of the EU 2009/33/EU.

Results. Today, the Ministry of Infrastructure of Ukraine recommends accounting for the fuel and lubricant consumption of buses using a method based on information about the basic linear fuel consumption rate of a transport vehicle and a number of adjustment factors, l/100 km

$$Q_F = 0.01 \cdot H_{BLF} \cdot S \cdot (1 + 0.01 \cdot K_\Sigma), \qquad (1)$$

where H_{BLF} is basic linear rate of fuel consumption, l/100 km; S is mileage of the vehicle, km; K_Σ is total adjustment factor, %.

For urban bus transportation, the following components of the adjustment factor are used: work in urban conditions (up to 15 %), work that requires frequent stops – 10 %, and the age of the bus (up to 9 %).

This approach does not take into account all the factors that affect the fuel consumption of buses during the transportation process in real conditions. It also does not allow carriers to assess the economic advantages of the express mode of traffic and warns against the operation of buses in the route taxi mode, especially in the central part of the city.

To study the effect of the number of stops on the route on the fuel consumption of buses, a mathematical model was developed based on the fuel balance equation of the vehicle. The structure of the developed model is given in the work [23].

Testing of the developed model was carried out on typical routes of the city of Dnipro. Information about the number of stops (where passenger exchange takes place) and additional dynamic loads, which are related to the level of occupancy of the bus cabin, were used as input data for modelling. These indicators were determined based on a survey of passenger flows. The values of the angles of the longitudinal slope of the road and the distances of the sections between the stops were determined with the help of the Internet resources Google Earth Pro and Google maps, respectively. The number of additional stops at traffic lights was calculated as a weighted average value according to the Bernoulli distribution.

For example, during the survey on route No. 29 (residential area Peremoha-6 – Lesya Ukrainka Avenue), which is operated by BAZ A81 buses operating as a shuttle taxi, the number of bus stops during the flight varied in the range from 25 up to 60 units. With this in mind, mathematical modelling of the transportation process was performed for the following number of stops: 42 and 69 stops that correspond to the conditions of operation of buses in route taxi mode; 30 stops that correspond to the operation of buses in normal (post-stop) mode; 15, 9 and 3 stops, which correspond to the operation of buses in express mode. The simulation results are presented in the Table 1 and in Fig. 1.

Analysis of the information given in Table 1 and in Fig. 1 shows that fuel consumption on route No. 29 is from 16.5 l/100 (at $n_{stop} = 3$) to 45.5 l/100 km (at $n_{stop} = 69$), and the very effect of the number of stops per 1 km of the route ($n_{stop}^{1\,km}$) on fuel consumption has a linear character and is approximated by dependence

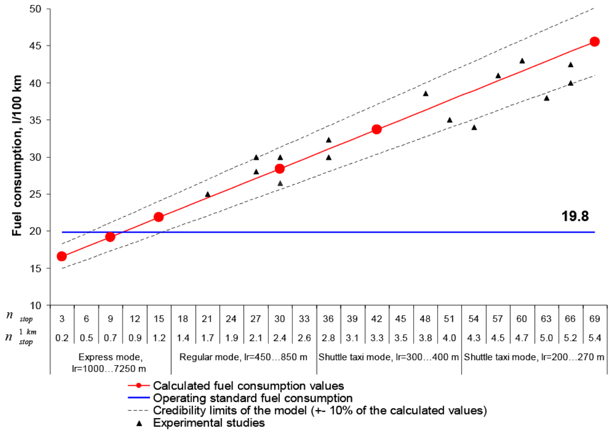

Fig. 1. Dependence of fuel consumption of buses on the number of stops on the route

$$Q_{l/100\,km}^{BAZ\ À81} = 15.214 + 6.366 \cdot n_{stop}^{1\,km}. \qquad (2)$$

Taking into account the mutual relationship between $n_{stop}^{1\,km}$ and the average length of the race on the route $(\bar{l}_r)$, it is advisable to present expression (2) in a form that is convenient to use for determining fuel consumption on any route

$$Q_{l/100\,km}^{BAZ\ À081} = 15.214 + 6.366 \cdot \left(\frac{L_r + \bar{l}_r}{L_r \cdot \bar{l}_r} \right). \qquad (3)$$

In turn, the normative operating fuel consumption of BAZ A81 buses according to the Ministry of Infrastructure of Ukraine is equal to 19.8 l/100 km (Fig. 1). Thus, the fuel consumption of buses operating in normal mode (n_{stop} = 30, $\bar{l}_r = 0.50$ km) exceeds the normative values by 42 %; and in the route taxi mode (n_{stop} = 42, $\bar{l}_r = 0.35$ km) by 70 %. Therefore, the introduction of an express traffic mode on the route will allow reducing fuel consumption by 23–42 % and increasing the speed of communication on the route by 20–43 % (Fig. 2).

The analysis of simulation results on other routes, on which different models of buses are operated, made it possible to clarify a relationship between the coefficients of models (2 and 3) and information about the basic linear rate of fuel consumption of vehicles (H_{BLF})

$$Q_{l/100\,km} = H_{BLF} \cdot \left[1.028 + 0.381 \cdot n_{stop}^{1\,km} \right]; \qquad (4)$$

$$Q_{l/100\,km} = H_{BLF} \cdot \left[1.028 + 0.381 \cdot \left(\frac{L_r + \bar{l}_r}{L_r \cdot \bar{l}_r} \right) \right]. \qquad (5)$$

Thus, established empirical dependencies (4 and 5) make it possible to estimate the energy resource efficiency of the vast

Table 1

Results of mathematical modelling variants of bus traffic modes

Indicator	Mode of operation of buses					
	shuttle taxi		regular	express		
Route length, L_r, km	14.5					
The number of stops on the route, n_{stop}, un	69	42	30	15	9	3
The average length of the race, $\bar{l}_r$, km	0.21	0.35	0.50	1.04	1.81	7.25
The number of stops per 1 km of the route, $n_{stop}^{1\,km}$, un/km	4.76	2.90	2.07	1.03	0.62	0.21
Connection speed, V_{bus}, km/h	13.5	17.1	19.3	23.2	25.2	27.6
Shuttle bus fuel consumption, Q_r, l/shuttle	6.60	4.88	4.12	3.16	2.78	2.40
Fuel consumption, $Q_{l/100\,km}$, l/100 km	45.5	33.6	28.3	21.7	19.1	16.5

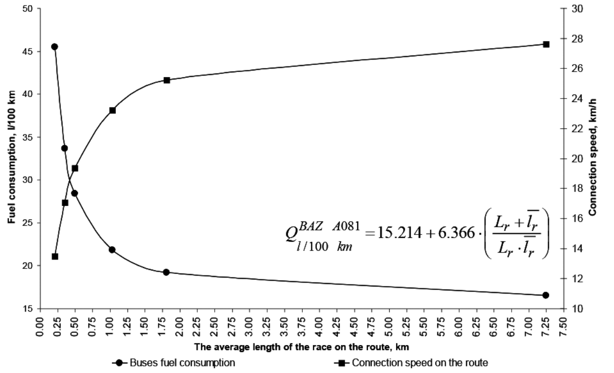

Fig. 2. The effect of the average length of the route on the fuel consumption of buses and the speed of the connection

majority of bus models depending on the traffic mode on city routes.

Thus, at the request of the operation service of the motor transport company LLC "DniproBas", according to the results of the survey of passenger flows in the morning "peak" hour, the feasibility of introducing an express mode on bus route No. 70 (Prydniprovsk – Staromostova Square) movement. The route consists of 27 stops, 25 BAZ A81 buses are operated on it, operating in regular mode. With the help of the developed method for determining the rational parameters of the express traffic mode [24], it was established that the maximum efficiency of the passenger transportation process on route No. 70 can be achieved with the following two variants of the combined mode with the express connection: (n_{stop} = 8, A^U = 12, A^E = 6) and (n_{stop} = 13, A^U = 8, A^E = 10), then mode No.1 and mode No. 2. This will free up 7 buses, reduce nonproductive transport work by 89 %, reduce the total costs of passengers for movement by 6 %, increase the speed of communication and the utilization ratio of the capacity of communication buses by 15 and 24 %, respectively.

The ecological effect of the introduction of the proposed combined traffic modes with express connection on route No. 70 will be observed due to the reduction of operational fuel costs. The calculation of emissions of pollutants was performed in accordance with the methodology for calculating emissions of pollutants and greenhouse gases into the air from vehicles (order of the State Committee of the State of Ukraine No. 452 of 11/13/2008), one year was chosen as the evaluation period.

Mass of spent fuel for the calculation period

$$M_{year} = Q^{fuel}_{day} \cdot D \cdot K, \tag{6}$$

where Q^{fuel}_{day} is operating fuel consumption on the route during the day; D is the number of working days of the route ($D = 270$); K is conversion factor into weight units of fuel, for diesel fuel $K = 0.85$ kg/l.

Fuel consumption on the route during the day

$$Q^{fuel}_{day} = \frac{L_r \cdot \psi^U_{day} \cdot Q^U_{l/100\,\text{km}}}{100} + \frac{L_r \cdot \psi^E_{day} \cdot Q^E_{l/100\,\text{km}}}{100}, \tag{7}$$

where ψ^U_{day}, ψ^E_{day} is the number of route performed by ordinary and express buses; $Q^U_{l/100\,\text{km}}$, $Q^A_{l/100\,\text{km}}$ – fuel consumption of buses operated in normal and express modes, respectively, l/100 km, is calculated as a function of the average length of the race on the route according to the obtained dependence (5).

To calculate the emissions of pollutants and greenhouse gases from motor vehicles, the specific emissions K^{SE} of pollutants into the atmosphere from the consumption of one ton of fuel and the influence coefficients K^{TC} of the technical condition of the motor vehicle (Table 2) are used, and the mass of the emissions of the E^{th}_j pollutant itself determined by dependence

$$E_j = M_{year} \cdot K^{SE}_j \cdot K^{TC}_j. \tag{8}$$

The results of calculations according to (6–8) are given in Table 2 and in Fig. 3.

Analysis of the performed calculations shows that as a result of the introduction of the proposed combined regimes, annual emissions of carbon dioxide CO_2 will be reduced by more than 200 tons, carbon monoxide CO by more than 4 tons, nitrogen oxides NO_x by more than 2 tons, and other pollutants by an average of 25 % in proportion to the reduction in total fuel consumption.

The economic assessment of the damage caused by the annual emissions of pollutants into the atmospheric air by vehicles on route No. 70 was determined in accordance with the Directive of the European Parliament and the Council of the EU 2009/33/EU [25]. The total value index of the annual economic loss was calculated according to [26]

$$Costs^{EUR}_{year} = \sum_{j=1}^{n} \varphi_j \cdot E_j \cdot 10^3, \tag{9}$$

Table 2

Volumes of pollutant emissions on route No. 70 for the settlement period

Pollutant	Group: passenger buses; type of fuel: diesel fuel		Acting technology $A^U = 25$	Mode No. 1 $n_{stop} = 8$, $A^U = 12$, $A^E = 6$	Mode No. 1 $n_{stop} = 13$, $A^U = 8$, $A^E = 10$
	K^{SE}_j, kg/t	K^{TC}_j			
M_{year}, kgr			294,678	221,611	219,070
E_{CO}, kg	37.4	1.5	16,531	12,432	12,289
E_{NMVOC}, kg	8.16	1.8	2,404	1,808	1,787
E_{CH_4}, kg	0.25	1.4	103	77	76
E_{NO_2}, kg	31.4	0.95	8,678	6,526	6,451
E_{FDSP}, kg	3.85	1.8	2,042	1,535	1,518
E_{NO}, kg	0.12	1.0	35	26	26
E_{CO_2}, kg	3 138	1.0	924,699	695,415	687,444
E_{SO_2}, kg	4.3	1.0	1,267	953	942
$E_{C_{20}H_{12}}$, kg	0.03	1.0	8.8	6.7	6.6

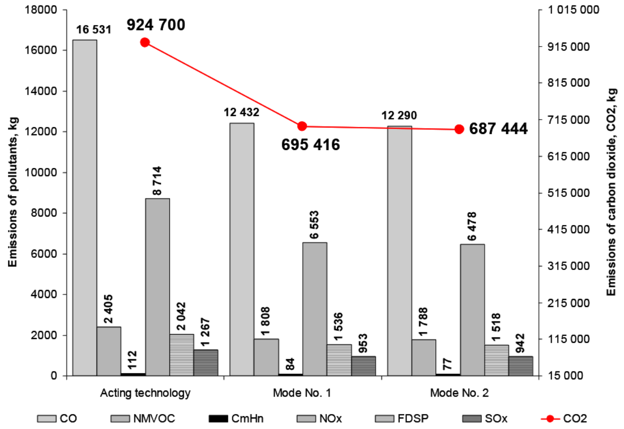

Fig. 3. Comparative characteristics of ecological indicators before and after the introduction of express traffic mode on route No. 70

where φ_j is specific value of emissions by road transport of the E_j^{th} polluting substance, Table 3 (for carbon dioxide CO_2 emissions, the coefficient is not applied).

The results of calculations according to (9) are shown in Fig. 4 and indicate that the implementation of combined modes with express connection will reduce environmental damage from pollutants by more than EUR 65,000 per year (according to the estimates of Directive 2009/33/EC of the European Parliament and the Council of the EU [25]), or more than UAH 2.7 million.

Conclusions. According to the classic definition of the "World Commission on Environment and Development", economic growth, social equality and environmental protection are defined as the main principles of sustainable development. Since modern passenger transportation is the sphere of human activity that affects environmental pollution, it should be considered within the framework of the paradigm of sustainable development. The results of the work prove that the use of an express mode of bus traffic is a proven alternative way of increasing environmental safety in a modern metropolis.

The suggested methodological approach is a universal algorithm that is proposed to be used by interested parties to assess the possibilities of reducing the negative impact of transport on the environment. The use of the developed approach in practice allows transport departments of city halls and akimats of megacities together with specialists of transport companies (developers of public transport routes) to reduce emissions of pollutants into the atmospheric air, achieving a minimal negative impact on the environment.

The adequacy and effectiveness of the proposed approach is confirmed by economic calculations in accordance with Directive 2009/33/EC of the European Parliament and the Council of the EU. It is substantiated that the implementation of combined modes with express connections will reduce environmental damage from pollutants by more than EUR 65,000 per year (calculations were made for route No. 70 in Dnipro).

Table 3

Specific cost of emissions by road transport [23]

CO_2, EUR/kg	NO_x, EUR/g	*NMVOC*, EUR/g	*FDSP*, EUR/g	CO, EUR/g	SO_x, EUR/g
0.035	0.0044	0.001	0.087	0.0003	0.0022

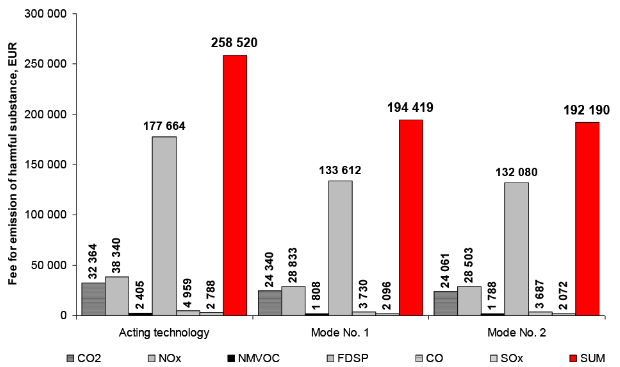

Fig. 4. Economic assessment of the damage caused by annual emissions of pollutants into the atmospheric air by vehicles on route No. 70

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Застосування експресного режиму руху як альтернативний шлях підвищення екологічної безпеки міста

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Мета. Запропонувати сучасний методологічний підхід визначення енергоефективності перевезень пасажирів міськими автобусами шляхом встановлення взаємозв'язку між витратами палива й кількістю зупинок на маршруті, а також екологічної оцінки запровадження експресного режиму руху автобусів в умовах сучасного мегаполісу.

Методика. Для побудови моделі дослідження енергоресурсної ефективності роботи автобусів у різних режимах руху використані рівняння паливного балансу транспортного засобу. Визначення критеріїв і обмежень, що обумовлюють ефективність експресного режиму руху автобусів, виконувалося методами системного аналізу. У якості вихідних даних при моделюванні використовувалися відомості про кількість зупинок (де відбувається пасажирообмін) і додаткові динамічні навантаження, що пов'язані з рівнем заповнення салону автобусів. Ці показники визначалися на підставі обстеження пасажиропотоків. Значення кутів поздовжнього ухилу дороги й відстаней ділянок між зупинками визначались за допомогою інтернет-ресурсів Google Earth Pro і Google maps відповідно. Кількість додаткових зупинок на світлофорах розраховувалася як середньозважене значення за розподілом Бернуллі. Для обґрунтування запровадження комбінованого режиму руху в розглянутому прикладі застосовані елементи функціонального аналізу. Економічна оцінка була проведена відповідно до Директиви Європейського парламенту й Ради ЄС 2009/33/ЄС.

Результати. У проведених дослідженнях надана екологічна та економічна оцінка запровадження експресного режиму руху автобусів в умовах сучасного мегаполісу. Результати проведених досліджень дозволили визначити залежність енергоресурсної ефективності роботи автобусів від різних режимів руху. Підвищення енергоефективності перевезень досягається за рахунок запровадження на міських маршрутах більш продуктивних і менш витратних режимів руху автобусів. Доведено, що найбільш ефективним є комбінований режим із використанням звичайного та експресного сполучення.

Наукова новизна. Автори вважають, що одним із дієвих заходів зменшення екологічних наслідків від експлуатації міського громадського автомобільного транспорту є підвищення енергоефективності перевезень. Цей висновок ґрунтується на тому, що одним із головних кількісних показників експлуатації транспортних засобів є витрати палива, які безпосередньо впливають на масу викидів забруднюючих речовин і залежать від режиму руху автобуса.

Практична значимість. Запропонований методологічний підхід є універсальним алгоритмом, що пропонується використовувати зацікавленим сторонам для зменшення негативного впливу транспорту на навколишнє середовище. Використання розробленого підходу на практиці дозволяє транспортним департаментам мерій та акіматів мегаполісів разом із фахівцями транспортних компаній (розробниками маршрутів руху громадського транспорту) знизити викиди забруднень до атмосферного повітря, досягнувши мінімального негативного впливу на навколишнє середовище.

Ключові слова: *транспортне обслуговування, режим руху, паливна економічність, шкідливі викиди, екологічна безпека*

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