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Evaluation of the impact of ambient temperature on fuel consumption by diesel and CNG buses

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Abstract. The paper is devoted to the problem of bus operation in various climatic, road and transport conditions. The reasons for replacing diesel buses with more environmentally friendly ones using natural gas are described. Experimental studies on the operation of large-class buses – LiAZ-529265 diesel bus and LiAZ-529267 CNG bus in an urban environment are given. The dependences of the influence of various ambient temperatures on fuel consumption are obtained, and mathematical models that describe these dependences are proposed. The range of studied temperatures is from minus 31°C to +37°C. As a result of driving experiments, it was found that the natural gas consumption of the LiAZ-529267 bus is 23-24% higher than that of the diesel counterpart under similar road and transport operating conditions. The deviation between the minimum and maximum values of diesel fuel consumption is 37-45%. For compressed natural gas, the deviations were 36-43%. However, the equivalent cost of purchasing natural gas is 52% lower than that of diesel fuel.

1 Introduction

Nowadays, the issue of rational use of energy resources is of particular importance in many countries of the world. This is caused by the fact that more than 80% of the produced energy is extracted through the use of non-renewable sources. At the same time, many countries that do not have enough of their reserves of oil, gas, coal, electricity, etc., depend on imports, which may affect their energy security. And against the background of the situation in the world that has changed in the last few years, there are interruptions in the supply chains of energy resources, which, in turn, leads to their significant rise in price. The situation is further aggravated by the fact that many developed countries are implementing the concept of a low-carbon society in order to minimize the harmful effects of anthropogenic pollution on the environment. However, it is necessary to develop alternative energy, which leads to additional costs.

One of the main industries that consumes a huge amount of energy and pollutes the environment is road transport. Therefore, more and more countries are expanding the use of alternative sources, including renewable ones, replacing traditional gasoline and diesel fuel. The main development areas of modern automotive industry are the creation of more

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environmentally friendly engines using electricity, natural gas, ethanol, hydrogen, etc. [Brdulak et al. 2020, Konoplev et al. 2020, Wei et al. 2018]. The countries of the European Union, Brazil, China, Norway, Russia, the USA, Japan, South Korea and, to a lesser extent, some others have government programs to reduce the share of the car fleet on conventional fuels.

For example, as of the end of 2021, Norway is the world leader in purchased electric vehicles, which account for about 50% of all sales. The fleet of electric and hybrid vehicles in this country is about 95% of the total. China, Germany and the United States sell the most electric vehicles in the world – 500 thousand units, 230 thousand units and 110 thousand units, respectively. In China, the USA and Japan, they produce some of the best-selling electric vehicles in the world – Wuling Hong Guang Mini EV, Tesla Model 3 and Nissan Leaf, respectively. China, the European Union and the USA are among the top three in terms of electric vehicle fleet. The global fleet, including PHEV hybrids, is about 16 million (at the end of 2021).

As for the use of natural gas, the global fleet of CNG vehicles amounted to more than 28.5 million as of the beginning of 2020. At the same time, the Asia-Pacific region, led by China, Iran and India, is the leader in the number of such vehicles (about 20.5 million units or 72% of general) [Current 2020].

If we consider the Russian market, then at present, the use of natural gas vehicles is optimal in comparison with other types of energy sources. This is due to a number of reasons:

- the world's largest methane reserves are concentrated in Russia (according to various estimates, from 19 to 24.5% of the global ones) [OPEC 2020, Statistical 2020], and the country is also in second place in terms of production of this hydrocarbon (16.5% of the global production) [OPEC 2020, Statistical 2021];
- the production of a number of cars, trucks and special vehicles, as well as buses using natural gas as fuel, including the use of Russian equipment, has been launched;
- the gas filling infrastructure is intensively developing in the regions of the country, in the construction of which Russian equipment is used;
- improvement of legislation and, on the basis of this, significant state subsidies for the purchase of CNG cars and the construction of natural gas vehicle filling stations;
- weak state subsidies and, in connection with this, low development of technologies for the domestic production of electric motors and hydrogen fuel engines;
- significantly higher cost of electric vehicles compared to CNG vehicles. For example, the cost of an electric bus is 3-4 times higher than the price of a CNG bus;
- the almost complete absence of service stations for electric vehicles and the complete absence of maintenance of hydrogen fuel vehicles;
- long charging time for batteries of electric vehicles (15-30 minutes) in comparison with natural gas vehicles (5-10 minutes);
- electricity generation is mainly carried out by burning fossil fuels.

It is known that in the big and largest cities of the world, due to high motorization, the main source of environmental pollution is road transport [Anisimov et al. 2017, Azemsha et al. 2018, Bezruchonak 2019, Chainikov et al. 2016, Chikishev et al. 2019, Chikishev et al. 2017, Fadyushin and Zakharov 2020, Hnatov et al. 2017, Karmanov et al. 2018, Kushchenko et al. 2020, Petrov and Svistunova 2022, Pistsov and Zakharov 2021, Todorut et al. 2020, Wang et al. 2018, Wang et al. 2020].

Thus, research related to the operation of transport in cities is an urgent task. Studies [Chikishev 2021, Giraldo and Huertas 2019, Glagolev et al. 2018, Gomez et al. 2021, Istrate et al. 2019, Kolesov and Petrov 2017, Özener and Özkan, 2020, Rosero et al. 2021, Yu et al. 2020] show that in urban environments, fuel consumption and the amount of emissions of harmful substances with exhaust gases are significantly affected by climatic, transport and road conditions, as well as by the design features of vehicles and their technical condition. For Russia and such countries as Denmark, Canada, Norway, the USA, Finland and Sweden, the climatic factor plays a special role, since air temperatures below zero prevail in most of these countries for a long time. Therefore, knowledge of the influence of this factor on the level of fuel consumption of cars can contribute to the rational planning of enterprises' costs for its purchase.

Many experimental works have been devoted to this issue [Chikishev and Chainikov 2022, Evtyukov et al. 2021, Kuharonak et al. 2020, Oprešnik et al. 2018, Özener and Özkan. 2020, Rosero et al. 2021, Savostin-Kosiak et al., 2020, Yu et al. 2020]. However, studies to identify patterns of the influence of ambient temperatures on natural gas consumption, in relation to Russian large-capacity buses, have not been identified. The choice of buses running on gas fuel is justified by the fact that, according to the data of the Russian federal state statistics service [Federal 2020], the share of buses running on natural gas increased from 5.4% in 2014 to 20.7% in 2020. At the same time, the number of gasoline buses from of the total number decreased from 59% in 2010 to 5.5% in 2020, and the number of diesel buses increased from 35.6% in 2010 to 69.9% in 2020. Thus, for comparison, the driving cycles of buses fueled by compressed natural gas and diesel fuel will be studied in this paper.

2 Methods

The aim of the work is to establish patterns of changes in fuel consumption of high-capacity low-floor buses operating on urban regular routes in the Russian city of Tyumen.

Research objectives:

- to conduct driving experiments on the influence of external operating conditions on the fuel consumption of buses running on compressed natural gas and diesel fuel;
- to identify patterns of influence of operating conditions on the fuel consumption of the studied buses;
- to carry out comparative calculations on the cost of purchasing gas and diesel fuels, taking into account actual operating conditions.

The object of research is the process of changing fuel consumption by buses in an urban environment. The subject of the study is Russian low-floor large-capacity buses LiAZ-529267 (CNG) and LiAZ-529265 (diesel), which are widely used on regular routes of Russian cities, including Tyumen. The buses comply with environmental class 5 (Euro-5). They have a total capacity of 108 people, of which 31 are seating. Brief comparative characteristics of buses are presented in table 1.

Table 1. Technical characteristics of LiAZ-529265 and LiAZ-529267 (CNG) buses

Bus brand	LiAZ-529265	LiAZ-529267 (CNG)
Engine	YaMZ 53633, SCR, E5	YaMZ -53624-40 CNG
Number and arrangement of cylinders	6-cylinder, in-line, vertical	
Engine capacity, cm3	6650	
Compression ratio	17.5±0.6	12.0±0.6
Overall dimensions (length, width, height), mm	11990 / 2500 / 2880 (with air conditioning – 2938)	
Engine power, h.p. (kW)	202 (275) at 2300 min^{-1}	210 (285.6) at 2300 min-1
Max. torque, N.m	1250 at 1300-1600 min^{-1}	1130 at 1100-1600 min-1
Fuel tank capacity (cylinders), l (m3)	220	
Power system type	accumulator with electronic control, with injection pressure:	

	180 MPa (1800 kgf/cm^2)	20 MPa (200 kgf/cm^2)
Wheel base, mm	5960	
Body type	low-floor, load-bearing, all-metal, wagon layout	
Permissible load on the front-rear axle, kg	6500/11500	
Main bridge	rear, Hande Axle	
Wheel arrangement	4x2	
Heating system	liquid, using the heat of the cooling system and an independent heater (WEBASTO). Interior heater – ZENITH-68000	
System of release and neutralization of gases	one muffler with integrated catalytic converter and SCR system	
Tires	275/70, R 22.5	
Maximum speed, km/h	85	
Transport (basic) fuel consumption rate, l (m3)/100 km	39.2	43.12
Engine oil used	Lukoil Avangard Professional 5w-30 – multi-grade	Lukoil CNG 5w/30 – multi-grade

Thus, it can be established that these bus brands are identical in terms of their main technical characteristics. The differences are only in the fuel used and the degree of compression in the working cylinders.

To reduce the influence of the variability of transport and road factors, driving experiments were carried out on regular city routes No. 14 and No. 25 on weekdays, non-holidays, on category I roads. The routes consist mainly of straight sections with a small number of slopes and turns, and there are no dangerous sections.

Route No. 14 "District hospital - st. Deputatskaya" connects the peripheral parts of the city with the center. The route scheme is shown in Fig. 1 a. Route No. 25 "st. Tallinnskaya – railway station" connects the peripheral parts of the city with the center, as well as with the railway station. The route scheme is shown in Fig. 1 b.

Fig. 1 a. Regular route No. 14 scheme

Fig. 1 b. Regular route No. 25 scheme

Route No. 25 is pendulum. The length of the route turnover is 27 km (in the forward direction – 13.1 km, back – 13.9 km). There are 24 stopping points in the forward direction, and 23 in the opposite direction. In the forward direction, there are 31 regulated intersections and 7 unregulated pedestrian crossings along the route. In the opposite direction, there are 32 regulated intersections and 7 unregulated pedestrian crossings. The turnover time in the interpeak time intervals is about 60 min. At peak times – up to 110 min. Route No. 14 is also pendulum. The length of the route turnover is 34.6 km (in the forward direction – 17.9 km, back – 16.7 km). There are 32 stopping points in the forward direction, and 30 in the opposite direction. In the forward direction, there are 41 regulated intersections and 6 unregulated pedestrian crossings along the route. In the opposite direction, there are 39 regulated intersections and 6 unregulated pedestrian crossings. The turnover time in the interpeak time intervals is about 80 min. At peak time – up to 130 min. When implementing driving cycles, the date, daily runs, the amount of fuel at the beginning and end of the route, and the actual average daily ambient temperature were recorded. The control of the actual fuel consumption is carried out by topping up the tank (cylinders) to the full. To reduce the influence of random and systematic errors on the obtained measurement results, more than 100 measurements of daily driving cycles were processed, which exceeds the number of measurements with the method used. The ambient air temperature was recorded daily based on daily averages according to the Gismeteo website. To reduce the influence of driving skills on the level of fuel consumption, data on buses on which two of the same drivers worked were taken into account (buses are operated in 2 shifts). To reduce the influence of the quality of diesel and gas fuel on the results of the experiment, the buses were refueled at the same gas filling station and natural gas vehicle filling station. The studied buses used lubricants and technical fluids, which are specified in the technical documentation of this brand. Tire types – YaShZ, size 275/70R22.5.

3 Experiment, data processing and analysis

As a result of processing driving experimental data along route No. 14, graphical dependencies were built, which are shown in Fig. 2.

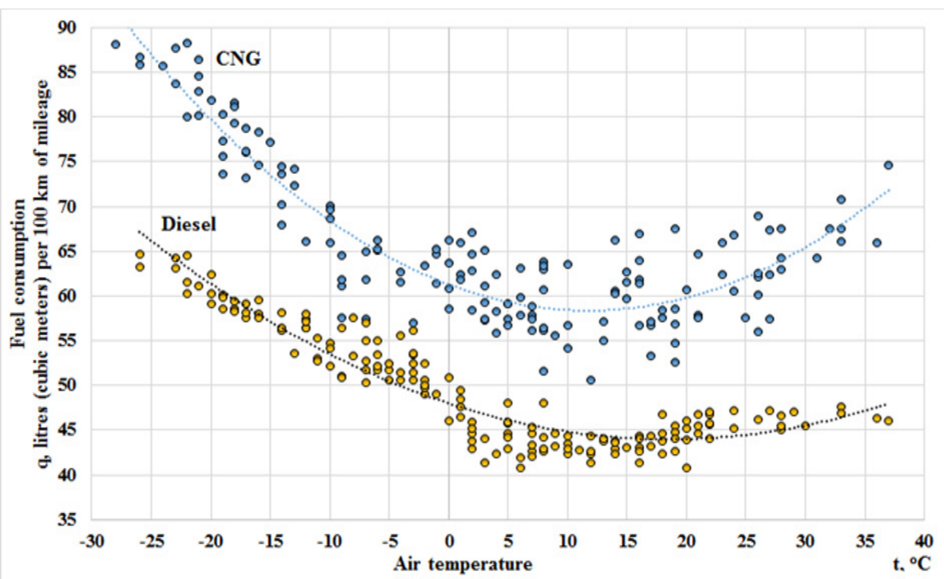

Fig. 2. Graph of the actual fuel consumption of the LiAZ-529265 diesel bus and the LiAZ-529267 CNG bus, reduced to 100 km of milage, taking into account the climatic, road and transport conditions on route No. 14

After analyzing the research data and Fig. 2 on the operation of a diesel bus, it was found that its daily mileage ranged from 99 to 179 km (mainly more than 150 km). The range of air temperatures during the study period was from minus 26 to +37 °C. The smallest deviation of diesel fuel consumption from the base values was observed in the air temperature range from +3 to +20 °C and amounted to about 41 l/100 km. And most of the fuel consumption values obtained at temperatures from +1 to +37 °C are in the range from 40.8 to 48.1 l/100 km. At air temperatures from 0 to minus 14 °C, fuel consumption mainly ranged from 49.1 to 58.2 l/100 km, and fuel consumption in the range from minus 16 to minus 26 °C amounted to 57.6 to 64.7 l/100 km. The minimum fuel consumption was obtained at an air temperature of +6 °C (40.8 l/100 km), and the maximum at minus 26 °C (64.7 l/100 km). The deviation between the minimum and maximum values was 37%. After analyzing the research data and Fig. 2 on the operation of a bus running on compressed natural gas, it was found that its daily mileage ranged from 77 to 230 km (mainly more than 200 km). The range of air temperatures during the study period was from minus 28 to +37 °C. The smallest deviation of natural gas consumption from the base values was found in the air temperature range from +8 to +19 °C and amounted to about 51 l/100 km. Most fuel consumption values at temperatures from minus 9 to +36 °C are in the range from 52.7 to 68.9 m^3/100 km. At air temperatures from minus 10 to minus 28 °C, fuel consumption has a stable growth and ranges from 65.9 to 88.3 m^3/100 km. The minimum fuel consumption was at an air temperature of +12 °C (50.6 m^3/100 km), and the maximum at minus 22 °C (88.3 m^3/100 km). The difference between the minimum and maximum values was 43%.

As a result of processing driving experimental data on route No. 25, graphical dependencies were built, which are shown in Fig. 3.

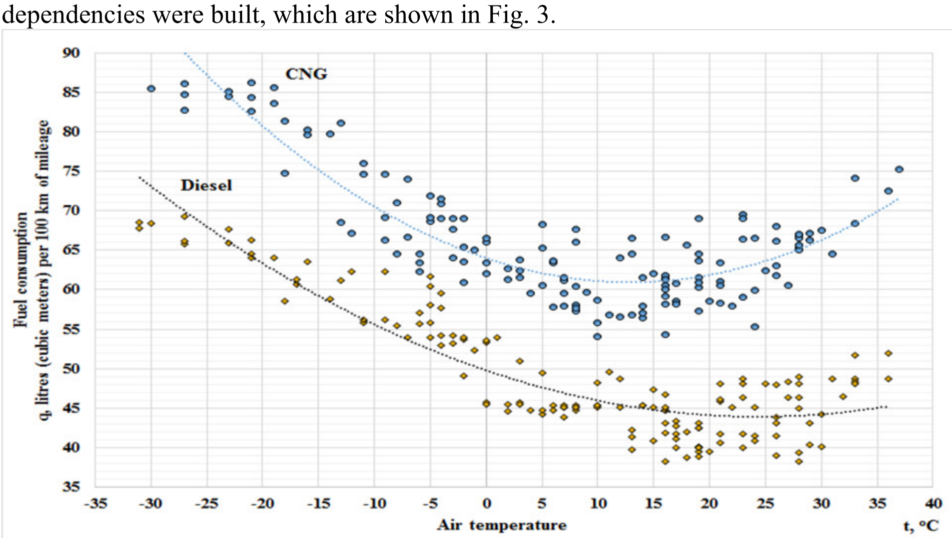

Fig. 3. Graph of the actual fuel consumption of the LiAZ-529265 diesel bus and the LiAZ-529267 CNG bus, reduced to 100 km of rmilage, taking into account the climatic, road and transport conditions on route No. 25

After analyzing the research data and Fig. 3 on the operation of a diesel bus, it was found that its daily mileage ranged from 83 to 215 km (mainly more than 200 km). The range of air temperatures during the study period ranged from minus 31 to +36 °C. The smallest deviation of diesel fuel consumption from the base values was observed in the air temperature range from +13 to +30 °C and amounted to less than 40 l/100 km. And most of the values of diesel fuel consumption obtained at temperatures from +2 to +36 °C ranged from 38.2 to 49.6 l/100 km. It should be noted that several values of fuel consumption were recorded in this range, which are below the transport (base) rate of 39.2 l/100 km. At air temperatures from +1 to minus 14 °C, fuel consumption mainly ranged from 52.3 to 62.3 l/100 km, and fuel consumption in the range from minus 16 to minus 31 °C was from 61.3 to 69.3 l/100 km. The minimum diesel consumption was recorded at an air temperature of +16 °C (38.2 l/100 km), and the maximum at minus 27 °C (69.3 l/100 km). The difference between the minimum and maximum values was 45%. After analyzing the research data and Fig. 3 on the operation of a bus running on compressed natural gas, it was found that its daily mileage ranged from 137 to 237 km. The range of ambient air temperatures during the study period ranged from minus 30 to +37 °C. The smallest deviation of natural gas consumption from the base values was observed in the air temperature range from +10 to +24 °C and amounted to about 54 m^3/100 km. Most gas consumption values at temperatures from minus 3 to +33 °C are in the range from 55.8 to 69.5 m^3/100 km. At air temperatures from 0 to minus 13 °C, fuel consumption mainly ranged from 60.9 to 76.0 m^3/100 km, and fuel consumption in the range from minus 14 to minus 30 °C was in the range from 79.7 to 86.3 m^3/100 km. The minimum gas consumption was recorded at an air temperature of +10 °C (54.1 m^3/100 km), and the maximum at minus 21°C (86.3 m^3/100 km). The deviation between the minimum and maximum values was 36%.

4 Conclusions

When processing driving experiments in the Excel and Statistica 8.0 software systems, quadratic mathematical models (1-4) are presented on the basis of the obtained patterns, and some numerical values of the main statistical characteristics are identified (Table 2).

$$q_{diesel\ 14} = 0.0115 * t^2 - 0.4391 * t + 47.959 \quad (1)$$

$$q_{CNG\ 14} = 0.0212 * t^2 - 0.4984 * t + 61.311 \quad (2)$$

$$q_{diesel\ 25} = 0.0099 * t^2 - 0.482 * t + 49.771 \quad (3)$$

$$q_{CNG\ 25} = 0.0183 * t^2 - 0.4716 * t + 64.012 \quad (4)$$

where *t* – actual average daily ambient temperature, °C.

Table 2. Statistical analysis of experimental mathematical models in the Statistica 8.0 software system

Mathematical model	Determination coefficient, R^2	Average approximation error, %	Fisher criterion F (0.95)	Student's t-test
$q_{diesel\ 25}$	0.81	4.5	302	26
$q_{diesel\ 14}$	0.88	3.5	348	36
$q_{CNG\ 25}$	0.79	6.2	86	39
$q_{CNG\ 14}$	0.84	6.8	103	40

By analyzing the values presented in table 3, it is established that the coefficient of determination from 0.79 to 0.88 indicates that the share of air temperature variations accounts for a large part compared to other factors affecting the change in fuel consumption. The statistical significance of the coefficients was confirmed by the values of Student's t-test. Since the average approximation error does not exceed 10%, the equations can be used as a regression. The value of the Fisher criterion at a confidence level of 0.95 in all cases is greater than the tabular value, therefore, the regression models adequately describe the effect of air temperature on the consumption of the studied types of fuels. It is known that the purchase of fuel takes up significant daily costs in the total cost of passenger transportation. Taking into account the study, based on the average values of fuel consumption in different temperature ranges (Table 3), the calculation of the costs of purchasing various types of fuels is given, taking into account their actual costs per 100 km (Table 4).

Table 3. Average values of fuel consumption in different temperature ranges l(m3)/100 km

Bus brand	Fuel type, un. meas.	Route No.	Temperature range, °C			
			-20…-15	-10…-5	+5…+10	+15…+20
LiAZ-529265	Diesel, l/100 km	14	59.1	53.2	44.0	43.8
LiAZ -529265	Diesel, l/100 km	25	61.6	57.3	45.4	42.2
LiAZ -529267	CNG, m^3/100 km	14	77.7	64.3	58.6	59.4
LiAZ -529267	CNG, m^3/100 km	25	80.9	68.2	60.7	61.1

As of February 2022, fuel prices in Tyumen are: diesel fuel – 56.43 rubles/l, compressed natural gas – 20.88 rubles/m^3.

Table 4. Fuel costs for the operation of buses, rubles/100 km

Bus brand	Fuel type	Route No.	Temperature range, °C			
			-20…-15	-10…-5	+5…+10	+15…+20
LiAZ-529265	Diesel	14	3335.01	3002.08	2482.92	2471.64
LiAZ -529265	Diesel	25	3476.09	3233.44	2561.92	2381.35
LiAZ -529267	CNG	14	1622.38	1342.59	1223.57	1240.27
LiAZ -529267	CNG	25	1689.19	1424.02	1267.42	1275.77

Comparing the actual fuel consumption, it can be established that it is higher with natural gas than with diesel fuel. On route No. 14, on average, by 23%, and on route No. 25 – 24%. Considering the difference in prices for liquid and gaseous fuels and calculating it in Table 5, it can be established that the cost of purchasing an equivalent volume of natural gas is on average 52% lower compared to diesel fuel.

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