ASSESSMENT OF ADAPTABILITY OF NATURAL GAS VEHICLES BY THE CONSTRUCTIVE ANALOGY METHOD

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ABSTRACT

This research is a comparative assessment of the operation of dual fuel engine vehicles (gas-diesel and diesel cycles) in the context of the fuel's environmental impact and economy. The influence of air temperature and vehicle load on this process is considered. The theory of constructive analogy as an example of natural gas vehicles is taken into account. The vehicles mentioned above were comparatively analyzed according to their level of adaptability to low ambient temperatures in the context of fuel consumption and exhaust gases emissions.

The regularities of the influence of low ambient temperatures and cargo weight on fuel consumption and the harmful substances emitted with the exhaust gases of natural gas vehicles were determined. In the range of negative air temperatures, the consumption of diesel fuel increased in comparison with a consumption of natural gas to 9%, and at positive temperatures, the consumption of gas increased up to 3%. Decreasing air temperature and cargo weight reduced the mass emissions of soot and the nitrogen oxide emitted with exhaust gases during operation, both on the diesel and gas-diesel cycles. Soot emissions decreased to 26% and nitrogen oxide to 54%.

The specific emissions of harmful substances emitted with exhaust gases per unit of fuel consumed for vehicles when operating on the gas-diesel cycle (GDC) is 14…33% less than on diesel.

When the ambient temperature falls to −38°C, the vehicle adaptability by fuel consumption when operating on the GDC increases on 6…18% in comparison with a diesel cycle. The vehicles' adaptability, assessed by harmful substances emitted with exhaust gases, to changes in cargo weight are almost identical.

Keywords: adaptability, fuel consumption, harmful substances emissions, natural gas vehicles variable low ambient temperature conditions.

1 INTRODUCTION

The steady operation of freight transport, involved in both long-distance and international transportation, consists of a set of components. One of the main components is the carrier cost. Fuel expenses occupy a leading role in the structure of the carrier cost; therefore, reducing fuel expenses is important.

The operation of transport in Russia and such countries as Finland, Canada, the northern regions of the United States, China and so on. mainly takes place in variable temperature conditions under which the indicators of the engine process change. This influences fuel consumption. Thus, when estimating fuel consumption, it is necessary to understand the conditions under which the vehicles were operated [1].

Variable temperature conditions influence the emissions of the major toxic components, nitrogen oxides and fuel soot [2,3]. It is necessary to understand the changes in these emissions under such conditions for the objective calculation of the environmental tax on vehicles [3].

Vehicle operating conditions can be divided into three groups: transport, road and climate. Because of the geographical arrangement of Russia, a considerable part of the country's vehicle fleet is operated under low-temperature conditions.

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Low-temperature conditions are those operating conditions under which the air temperature is lower than the norm. Standard operating conditions according to State Standard GOST 14846-81 [4] refer to the conditions under which the assessment of new vehicles' quality indicators is made. These conditions correspond to air temperature of 298 K (25°C); barometric pressure of 100 kPa (750 mm of mercury); relative humidity of air of 36% (pressure of water vapour of 1.2 kPa (9 mm of mercury); wind speed of unbelief, a calm; fuel temperature of 298 K (25°C); diesel fuel (DF) density of 0.85 t/m^3 and the road with a smooth asphalt concrete covering [4].

Operating experiences with vehicles shows that real conditions, as a rule, differ from standard conditons. Changing the operating conditions has considerable impact on vehicles' quality indicators, including fuel consumption and the amount of harmful substances emitted with exhaust gases (HSewEG), which eventually affect the carrier cost.

The solution to the carrier cost reduction problem and improvement of the economy of commercial vehicles can be achieved by the conversion of engines from operating on DF to a gas-diesel cycle (GDC) using compressed natural gas (CNG) and developing a more flexible approach to account for the fuel consumption under variable temperature conditions [5–14]. However, previous studies did not consider the influence of the ambient temperature on the fuel consumption and HSewEG of CNG/diesel dual-fuel engine vehicles. The GDC is understood as a process of gas mixture formation at which 75% of natural gas and 25% of an ignition dose of the diesel are used. The ignition dose of DF is necessary for ignition of the gas mixture, since natural gas does not ignite from compression.

In this regard, the purpose of this investigation is to assess the influence of low temperatures on vehicle fuel consumption, smoking of the exhaustand NO_x emissions when operating the trucks on diesel cycle (DC) and GDC (ignition dose of DF and CNG), depending on the degree of load capacity use.

2 METHODOLOGY

The process of changing fuel consumption, the content of nitrogen oxides and soot in exhaust gases (EG) of vehicles corresponding to ambient temperature and cargo weight change was thoroughly investigated for the Russian gas-diesel trucks KamAZ-43253, KamAZ-5320, KamAZ-65117, URAL-4320, URAL-44202, ZiL-5301.

2.1 Fuel consumption and emissions of HSewEG

The engine was warmed up to operating temperature. Measurement of vehicle fuel consumption was performed according to GOST 20306-90 [15]. Exceptions were made to the requirements of the ambient air temperature and cargo weight that changed in the experiment.

According to the experimental technique, studies were carried out under the following conditions:

- The vehicle moved on the highway with a smooth and dry asphalt surface;
- The length of an experimental distance was 10 km;
- Vehicle speed was 70 km/h, since that is an allowed speed for trucks on highways in Russia;
- The studied ambient temperatures ranged from plus 26.2°C to –38.3°C;
- The load of the engine was provided with changes of the cargo weight, expressed through load factor γ from zero to a nominal value;

- The measurement of DF consumption was performed by the 'topping up the tank to full' method with application of BNM-3/30 electronic scales (a measurement error of ± 5 g);
- CNG consumption was measured by the 'pressure drop on the manometer' method using the reference tables RD 3112199-1095-03 [16];
- The volume concentration of nitrogen oxide (NO_x) emission in the vehicle's (EG) was measured by a GIAM-27-04 gas analyzer with BV-1 during the operation of the engine without loading at a crankshaft speed of 2000 rpm^{-1}. Recalculation of the volume concentration of NO_x emission normalized to NO_2 to mass concentration accounted for data on the valid consumption of air and fuel, engine capacity and environmental parameters (barometric pressure, temperature and relative humidity). For this purpose, according to the obtained data on the fuel consumption of vehicles, thermal calculations of the engine during this work on the DC and GDC were made;
- EG smoke was measured by an INA-109 smoke meter according to GOST R 41.24-2003 and according to rule №24 of UNECE [17] (a measurement error ± 2%);
- Air temperatures were measured by the Checktemp 1 thermometer (measurement accuracy: in a range from minus 20 to plus 90°C it is equal to ± 0.3°C, and out of this range it is equal to ± 0.5°C;
- Atmospheric pressure was determined by a BM-2 barothermohygrometer (atmospheric pressure measurement error is ± 2 mm of mercury and relative humidity, is ± 5%).

As a result of the experimental studies on the assessment of HSewEG of vehicles and a comparison of the obtained data with the results of analytical calculation, we observed a sufficiently high level of data convergence. The divergence in NO_x emission values varies in the range of 4%–13%, in the emission of soot by 3%–11%, but, in general, the nature of the change of the point distribution has similar dependence. In this regard, the amount of harmful substances (HS) in EG was determined analytically by the well-proven techniques [18–20] on the basis of the valid values of fuel consumption for the established movement of vehicles with a speed of 70 km/h in low-temperature conditions when changing the cargo weight.

2.2 Vehicle adaptability

Experience with various brands and vehicle models demonstrates that their quality indicators, such as fuel consumption and HSewEG, changed in low-temperature operating conditions due to the various vehicles' adaptability. Vehicle adaptability is the ability to keep the values of quality measurements and efficiency measurements at their nominal level while there is a deviation to operation conditions from standard conditions [21].

The solution of the problem of vehicle adaptability to operating conditions allows us to correct the objectively normalized value of fuel consumption on cargo transportation and charging for environmental pollution by HSewEG.

To estimate vehicle adaptability to low-temperature operating conditions on the basis of fuel consumption and EG toxicity, one must define the vehicle's ability to provide standard values for fuel consumption and pollutant emissions under such conditions. One part of the adaptability quantitative index is the adaptability coefficient (A) [22]. It shows how many times the value of an indicator of quality and efficiency under given conditions differs from the base value. The theoretical borders of the adaptability coefficient are from 0 to 1; the closer the adaptability coefficient to 1, the better the adaptability. Thus, vehicle adaptability (A) as the ambient temperature changes (t) can be defined by the following formula [23]:

$$A = \frac{q_n}{q_a}, \tag{1}$$

where:
q_n – nominal fuel consumption value in standard conditions, l/100 km (m^3/100 km);
q_a – actual fuel consumption in the given conditions, l/100 km (m^3/100 km).

Assessing the vehicle's adaptability to low-temperature operating conditions by fuel consumption and emissions of HSewEG when performing transport work is proposed by using the following relationships (formulas (2) and (3)):

$$A_G = A_\gamma - S_t^A \cdot \left(t_o - t\right)^2 - S_\gamma^A \cdot \gamma, \tag{2}$$

where:
A_G – adaptability coefficient by fuel consumption;
A_γ – adaptability coefficient at equality of the actual and optimum air temperatures when a vehicle moves without cargo;
S_t^A – sensitivity parameter to ambient temperature change by adaptability coefficient, 1/°C^2.
t_o – optimal ambient temperature, °C;
t – actual ambient temperature, °C;
S_γ^A – sensitivity parameter to mass of transported cargo by adaptability coefficient;
γ – load factor.

$$A_{HS} = A_\gamma - S_t^A \cdot t - S_\gamma^A \cdot \gamma, \tag{3}$$

where:
A_{HS} – adaptability coefficient by HS;

3 RESULTS AND DISCUSSION

3.1 Analysis of fuel consumption

Based on the data obtained on the influence of ambient temperature on fuel consumption, the graphic dependence presented in Fig. 1 was constructed. Figure 1 provides data on the fuel consumption of the gas-diesel KAMAZ-5320 vehicle with the KAMAZ-7409.10 engine, whose technical characteristics are presented in Table 1. The size of an ignition dose of DF during the running of the vehicle on GDC in the ambient temperature range from + 26.2 to − 38.3°C, load factor from 0 to 1, changed from 0.1 to 0.3 l/100 km.

After analyzing the experimental results presented in Fig. 1, it is possible to make the following conclusions.

Natural gas, composed basically of methane (CH_4), has good miscibility with air to form a homogeneous combustible mixture. During the operation on GDC when applying DF, a zone of a flammable and enriched fuel mixture is formed. The intake of the homogeneous air–gas mixture into the cylinders of the engine promotes an increase in combustion pressure and leads to the strong ignition of the air–gas mixture, simultaneous with an igniting amount of

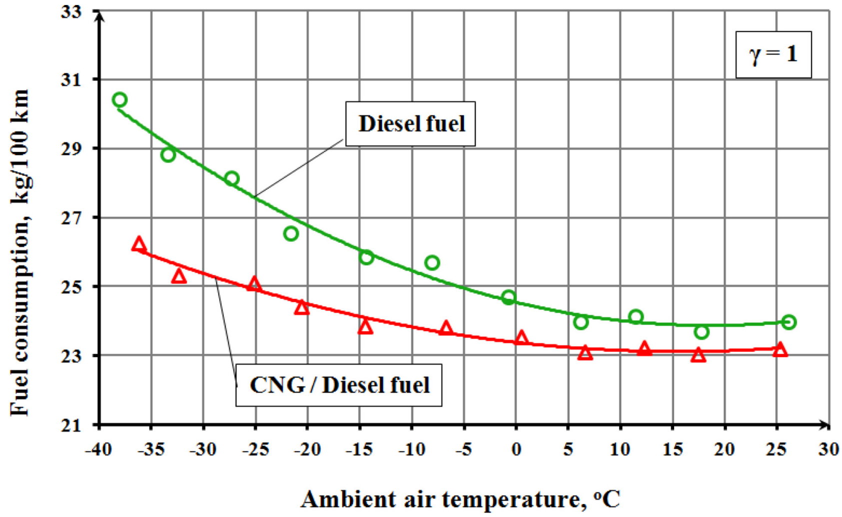

Figure 1: Influence of ambient temperature on fuel consumption of KAMAZ-5320 when operating on DC and GDC.

Table 1: Technical characteristics of natural gas vehicles.

Index	KamAZ -5320	KamAZ-65117	KamAZ-43253	URAL-4320	URAL-44202	ZiL-5301
	Value					
Carrying capacity, kg	7,500	14,000	7,500	5,000	8,100	3,450
Gross vehicle weight, kg	15,300	23,050	14,600	8,325	17,300	6,950
Engine type	V-engine	V-engine	V-engine	V-engine	V-engine	In-line
The number of engine cylinders, pcs	8	8	8	8	6	4
Engine power, kW (h.p.)	154 (210)	191 (260)	176 (240)	154 (210)	169 (230)	(136)

DF. When switching to the GDC, the percentage of fuel burning increases during the initial period, resulting in a reduction of the heat loss ratio in this combustion phase. This leads to an increase of the active heat generation coefficient, which predetermines more effective usage of heat in the cylinders during the initial combustion period. Therefore, the combustion pressure of the air–fuel mixture increases. The indicated efficiency appears to be almost identical here, as well as in the diesel process. When the ambient temperature falls from 0 to –38°C, the process of mixing and intensification of DF combustion is disrupted and the CNG combustion efficiency remains almost constant. When the ambient temperature falls, the viscosity of DF increases, deteriorating its spray ability and evaporation. The temperature reduces at the end of the compression stroke, the rate of pressure rise increases, and as a result, combustion is incomplete. Gaseous fuel practically does not change its physical and chemical properties when the ambient temperature falls. The quality of atomization and combustion intensification varies slightly, so the combustion of the combustible mixture in the engine cylinders is more complete and effective. Therefore, to overcome the forces of vehicle movement resistance, the engine, during operation on GDC, requires less work, resulting in lower fuel consumption.

Moreover, it is necessary to consider that vehicle loading affects fuel consumption.

The influence of low-temperature operating conditions and cargo weight on fuel consumption can be described by the following mathematical model:

$$q = q_{\min} + S_t^q (t_o - t)^2 + S_\gamma^q \cdot \gamma, \tag{4}$$

where:

q_{min} – minimum fuel consumption at equality of the actual and optimum ambient temperatures when vehicle moves without cargo, kg/100 km;

S_t^q – sensitivity parameter to changes in ambient temperature at the engine inlet by fuel consumption, kg/(100 km·°C^2);

S_γ^q – sensitivity parameter to changes in mass of load by fuel consumption, kg/(100 km).

3.2 The analysis of emissions of HSewEG

As a result of experiments on the influence of ambient temperature on emissions of soot and NO_x, Figs 2 and 3 were constructed.

The decrease in the mass emissions of NO_x as the ambient temperature falls can be explained in the following way: the temperature and pressure of the air charge affect both the amount of air supplied to the cylinder and the initial temperature of the air charge in the cylinder.

Ultimately, this will determine the amount of cold parietal areas, the pressure in the cylinder and the burning temperatures of the first fuel portions.

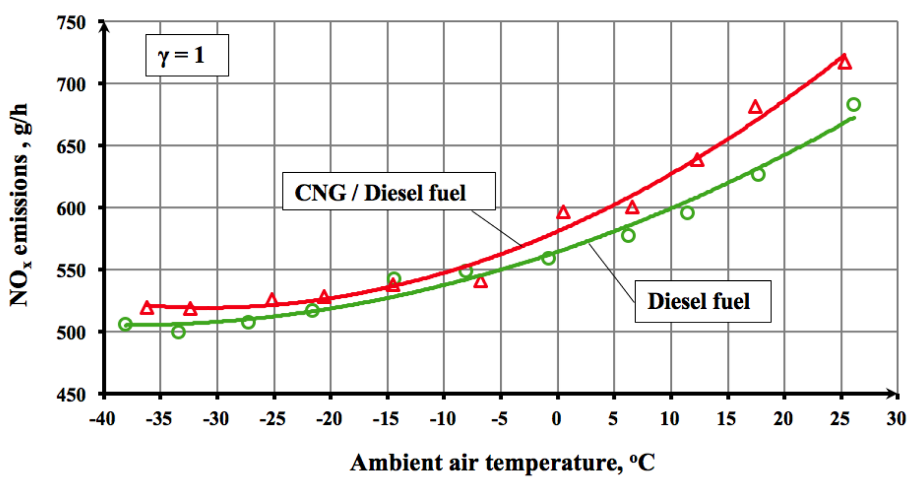

Figure 2: Influence of ambient temperature on NO_x emissions of KAMAZ-5320 when operating on DC and GDC under full vehicle loading.

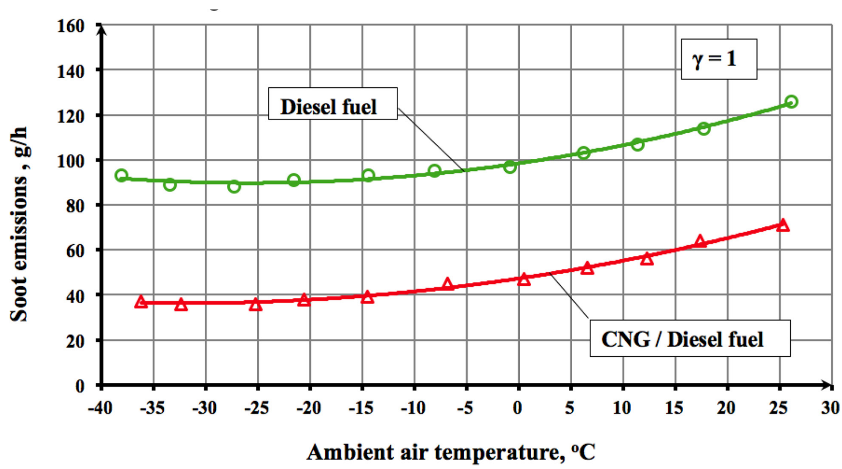

Figure 3: Influence of ambient temperature on soot emissions of KAMAZ-5320 when operating on DC and GDC under full vehicle loading.

Colder air entering the engine leads to a decrease in the engine operating cycle temperature, which reduces the emissions of nitrogen oxides due to the thermal nature of their formation. However, in the gas-diesel combustion, the combustion value of the fue–air mixture is greater than when the engine is operating on diesel, and therefore the combustion temperature of the fuel–air mixture is higher, which leads to some increase in the concentration of nitrogen oxides in the EGs.

Less fuel soot during the GDC can be explained by the fact that a higher combustion value of the fuel–air mixture leads to more complete combustion than the diesel process. Therefore, the quantity of unburnt solid carbon particles (the main component of fuel soot) is smaller.

When increasing the cargo mass, the difference between soot emissions in DC and GDC increases, because the relative displacement of DF by gas scales up when it is used for ignition because its injection rate remains constant and the regulation of loading is carried out by varying the amount of natural gas supplied to the engine cylinders.

The decrease in the mass emissions of soot when the ambient temperature falls is related to the increase in the weight charge and the excess air coefficient in the cylinder. The absolute oxygen concentration in the combustion chamber increases, contributing to faster and more complete fuel combustion.

The mathematical models describing the regularities revealed are as follows:

$$M_s = M_\gamma^S + S_t^S \cdot (t_o - t)^2 + S_\gamma^S \cdot \gamma, \quad (5)$$

where:

M_γ^S – mass emission of soot at equality of the actual and optimum ambient temperatures when vehicle moves without cargo, g/h;

S_t^S – sensitivity parameter to changes in ambient temperature by emission of soot, g/(h ·°C²);

S_γ^S – sensitivity parameter to changes in mass of load by emission of soot, g/h;

$$M_{NO} = M_\gamma^{NO} + S_t^{NO} \cdot (t_o - t)^2 + S_\gamma^{NO} \cdot \gamma, \quad (6)$$

where:

M_{γ}^{NO} – mass emission of NO_x, reduced to nitrogen dioxide NO_2 at equality of the actual and optimum ambient temperatures at car movement without cargo, g/h;

S_t^{NO} – sensitivity parameter to changes in ambient temperature by emission of NO_x, g/(h ·°C^2);

S_{γ}^{NO} – sensitivity parameter to changes in mass of load by emission of NO_x, g/h;

3.3 Vehicle adaptability analysis

With fuel consumption values at a specific ambient temperature, it is possible to construct a graphical dependence of the adaptability coefficient changes under different ambient temperatures (Fig. 4).

Considering the HSewEG values under a concrete ambient temperature, it is possible to construct the graphical dependence of the adaptability coefficient change under different ambient temperatures (Fig. 5).

The different adaptabilities of vehicles with the same engines can be explained by the different vehicle configurations, as well as by different engine room configurations.

Applying the constructive analogy theory described in [24–26], it is possible to determine vehicle adaptability levels under low-temperature operating conditions by fuel consumption and HSewEG.

When carrying out the analysis, analytical and experimental studies identified structural factors that affect the air and fuel temperature at the engine inlet, which in turn influences the formation of HSewEG and fuel consumption. These factors are:

- vehicle engine room configuration (motor hood, cab-over-engine);
- the place of an air intake (from under the motor hood, outside);
- existence of a radiator heater or blinds;
- heating of air; and
- heating of fuel.

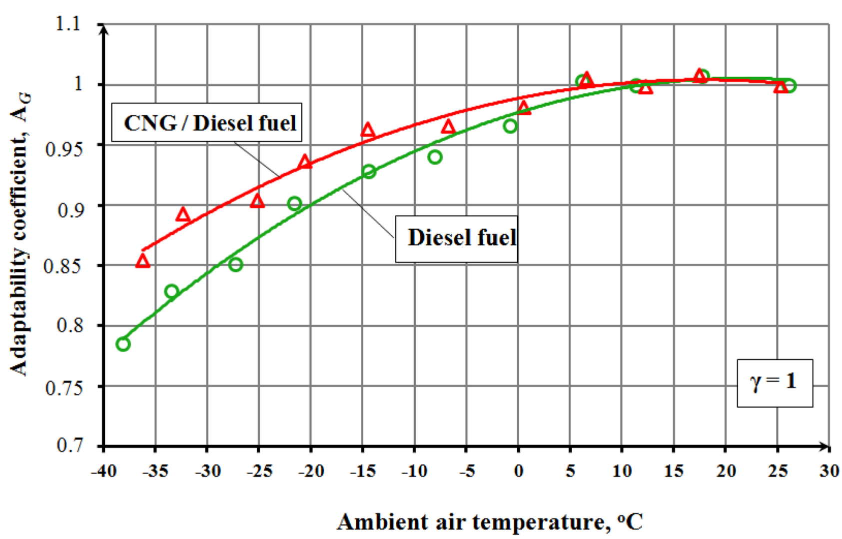

Figure 4: Influence of ambient temperature on the adaptability coefficient by fuel consumption of KAMAZ-5320 when operating on DC and GDC under full vehicle loading.

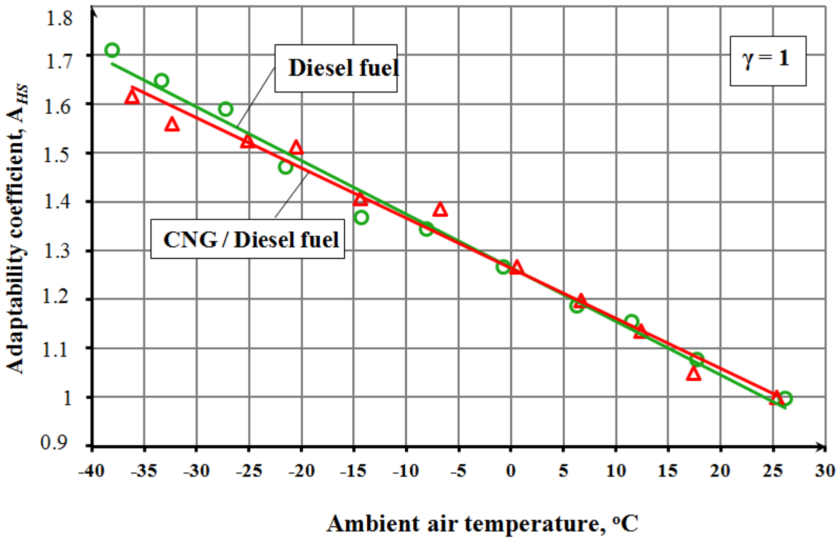

Figure 5: Influence of ambient temperature on the adaptability coefficient by HS emissions of KAMAZ-5320 when operating on DC and GDC and full vehicle loading.

In the cab-over-engine configuration, air is drawn in from the outside and no heating of the air charge increases the vehicle adaptability's by the HSewEG and reduces their adaptability level by fuel consumption. The existence of fuel heating and work on gaseous fuel affects the adaptability level.

The breakdown by adaptability level – high, medium, or low – was based on the values of coefficient A (1) by fuel consumption and HSewEG.

$$0 \leq A < 0.33 \text{ - low, } A_{av} = 0.17;$$

$$0.33 \leq A < 0.67 \text{ - the average level, } A_{av} = 0.5;$$

$$0.67 \leq A < 1.00 \text{ - high level } A_{av} = 0.84.$$

A_{av} – the average value of the coefficient A.

After a constructive analysis of the studied vehicle, it is possible to determine its adaptability level to low-temperature operating conditions by the EG toxicity and fuel consumption.

Table 2: Truck adaptability to low-temperature conditions by fuel consumption.

Adaptability level	Fuel type	
	Diesel	Gas-diesel (CNG)
High, $A_{av} = 0.84$	KamAZ-43253,	KamAZ-65117, KamAZ-43253,
Middle, $A_{av} = 0.50$	KamAZ-65117, URAL-4320, URAL-44202	URAL-4320, URAL-44202
Low, $A_{av} = 0.17$	ZiL-5301	ZiL-5301

Table 3: Truck adaptability to low-temperature conditions by HSewEG.

Adaptability level	Fuel type	
	Diesel	Gas-diesel (CNG)
High, $A_{av} = 0.84$	KamAZ-65117, KamAZ-43253,	KamAZ-65117, KamAZ-43253, URAL-44202
Middle, $A_{av} = 0.50$	URAL-4320, URAL-44202	URAL-4320
Low, $A_{av} = 0.17$	ZiL-5301	ZiL-5301

Truck adaptability to low-temperature conditions by fuel consumption can be estimated using the adaptability levels (Table 2).

Truck adaptability to low-temperature conditions by HSewEG can be estimated using the adaptability levels, too (Table 3).

4 CONCLUSIONS

The regularities of the influence of low ambient temperatures and cargo weight on fuel consumption and HSewEG of natural gas vehicles are revealed. In negative ambient temperatures, the DF consumption increases, in comparison to natural gas, up to 9%, and conversely, at positive temperatures, the consumption of gas increases up to 3%. Lowering the ambient temperature and cargo weight reduces the mass of soot and nitrogen oxide emissions from the EG when operating vehicles, both in DC and GDC; soot emissions are reduced to 26%, nitrogen oxide to 54%.

The regularities of changes in the amount of HSewEG from the fuel consumption of natural gas vehicles in the low-temperature operating conditions, taking into account the cargo weight, are revealed. Specific emissions of HSewEG per unit of fuel consumed at the KamAZ-5320 when working on GDC are 14%–33% less than on DC.

On the basis of the adaptability theory, the vehicle adaptability to variable operating conditions (ambient temperature and cargo weight) is defined by fuel consumption, smoke and NO_x emissions when operating on DC and GDC. It is revealed that the engine room configuration and peculiarity of the air inlet into the engine influence the adaptability level. The influence of the vehicle load has a linear character.

The regularities of changes in the adaptability coefficients of natural gas vehicles to low-temperature operating conditions and cargo weight by the fuel consumption and emissions of HSewEG are revealed. When ambient temperatures fall to −38°C, the adaptability of KamAZ-5320 assessed by fuel consumption when operating on GDC increases by 6%–18% compared to DC. The adaptability of KamAZ assessed by emissions of HSewEG to changes in ambient temperature is 3–11% more than at the Urals. Changes in the cargo weight, however, showed almost identical adaptations in both cars.

The results obtained on the basis of constructive analogy method, allowed to divide vehicles according to adaptability levels. Fuel consumption and norms of HSewEG emissions should be administered differentially depending on adaptability level, taking into account the actual ambient temperature.

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