Prospects for energy efficiency improvement and reduction of emissions and life cycle costs for natural gas vehicles

A V Kozlov¹, A S Terenchenko, V A Luksho and K E Karpukhin

Federal State Unitary Enterprise Central Scientific Research Automobile and Automotive Institute "NAMI" (FSUE «NAMI»), 125438, Avtomotornaya Street, 2, Moscow, Russia

E-mail: a.kozlov@nami.ru

Abstract. This work is devoted to the experimental investigation of the possibilities to reduce greenhouse gas emissions and to increase energy efficiency of engines that use natural gas as the main fuel and the analysis of economic efficiency of use of dual fuel engines in vehicles compared to conventional diesel. The results of experimental investigation of a 190 kW dual-fuel engine are presented; it is shown that quantitative and qualitative working process control may ensure thermal efficiency at the same level as that of the diesel engine and in certain conditions 5...8% higher. The prospects for reduction of greenhouse gas emissions have been assessed. The technical and economic evaluation of use of dual fuel engines in heavy-duty vehicles has been performed, taking into account the total life cycle. It is shown that it is possible to reduce life cycle costs by two times.

1. Introduction

The Natural gas (NG) is the most prospective alternative fuel used under the conditions of the Russian Federation. Use of natural gas allows obtaining high operating and economic parameter values, as well as fighting against noise pollution [1-3]. This fuel with the methane content of over 90% may be designated as environmentally safe, as it contains almost no aromatic hydrocarbons or sulfur compounds, which is of high importance in the context of reduction of smoke level and emissions of particulate matters with the exhaust gas [4-7].

The issues of using natural gas in motor vehicles are strategic and being successfully solved all over the world [8], particularly, in the Russian Federation as well [9].

Focusing on wider use of natural gas in motor vehicles will allow increasing the efficiency of fuel and energy conversion and reducing negative environment impact [10].

Currently, gas engines for motor vehicles with the gross weight of more than 3.5 t are being built on a diesel basis, because there are no gasoline engines with spark ignition of such displacement, which could be used as a base for conversion [11].

The main focus area of engineering solutions is adaptation of the diesel design for operation powered by alternative types of fuel (natural gas, etc.) and their combinations with conventional fuel in order to reduce fuel consumption, improve environmental, technical and economic characteristics of engines and to increase their competitiveness [12].

There are several ways to convert diesel engines for operation powered by gas fuel. One of the solutions for the task of extension of gas fuel use in motor vehicles is dual-fuel engines, which are capable of operation powered by conventional diesel fuel (DF) and alternative (gas) fuel [13]. It is the
most efficient way to use such engines in heavy-duty trucks and vehicles servicing inter-city and long-distance transport, especially, for vehicles operating under severe conditions, with the possibility to recover the expenses for their conversion and to widely use them both in close vicinity to natural gas vehicle refill stations and far away from the latter [14].

The peculiar properties of the dual-fuel engine working process enable obtaining the best economic effect at medium and high loads and provide the possibility to operate by diesel fuel when using up all the gas in the tank. The diesel engine operating according to the dual-fuel cycle is also a prospective solution in terms of reduction of nitrogen oxide and particulate matter emissions, while requiring marginal design updates [15, 16].

Therefore, dual-fuel engines may be considered as one of the efficient solutions for the use of compressed natural gas in motor vehicles with diesel engines [17].

Acceptable economic and environmental parameters of the dual-fuel engine may be reached by extension of the maximum optimizing control range (air/fuel ratio, pilot portion fuel amount, injection timing), application of phased multipoint gas injection and mixed quantitative and qualitative power control. In this regard, investigations with the purpose of optimizing these parameters have been performed.

2. Investigation subject and objectives

The investigation subject was diesel engine YaMZ-6566 with common rail fuel system, which operates according to the dual-fuel cycle with diesel fuel pilot portion and is equipped with the system of multipoint injection of gas into intake manifold developed by FSUE "NAMI". The characteristics of these engines are given in Table 1.

| Basic characteristics | Values |
|-----------------------|--------|
| Engine code designation given by the manufacturer | YaMZ-6566 |
| ICE version | Diesel engine | Dual-fuel engine |
| Engine displacement, l | 11.15 |
| Operating cycle | Four-stroke |
| Engine cylinder number and arrangement | V6 |
| Compression ratio | 17.5 |
| Cylinder bore, mm | 130 |
| Piston stroke, mm | 140 |
| Fuel | Diesel | Diesel and Natural gas |
| Maximum power, kW | 200 (at 1900 min⁻¹) | 197 (at 1900 min⁻¹) |
| Maximum permissible engine speed, min⁻¹ | 2100 |
| Maximum torque, N·m | 1170 (at 1100-1500 min⁻¹) | 1150 (at 1100-1500 min⁻¹) |

A gas supply system and a control system, ensuring operation in accordance with the dual-fuel cycle with ignition of the air-fuel mixture by the diesel fuel pilot portion, were installed onto the engine. The gas supply is phased multiport (6 gas injectors), the quantitative control of the air supply was performed by an electronic throttle.

The peculiar feature of the dual fuel engine is that two fuels, which differ in their physical and chemical properties and require different conditions for the optimized operation within the cylinder, are used in the working process. Given the fact that in terms of maximum economic efficiency natural gas (methane) shall be the main fuel in the dual-fuel process, the working process conditions shall be formed considering the optimization of combustion of this gas fuel.
The objective of this investigation was the comparative analysis of technical and economic parameters of the engine when operating using diesel fuel and according to the dual-fuel cycle during the engine bench tests and the total life cycle assessment.

3. Results of engine investigations on test bench

The optimized and efficient natural gas combustion is known to be reached at certain air-fuel ratio. Therefore, the works on adjustment of the optimized value of the air-fuel equivalence ratio ($\alpha$) ensuring full and efficient methane combustion on the one hand and stable ignition of the minimum diesel pilot portion on the other hand, were performed in the first phase.

The dependence between the reduced specific fuel consumption (specific diesel and natural gas consumption, reduced to the diesel fuel lowest heat of combustion) and the air-fuel equivalence ratio $\alpha$ is shown in Figure 1.

It has been found that the efficiency of the engine operation in dual-fuel cycle with the minimum values of reduced specific fuel consumption is reached when $\alpha$ is maintained within the range from 1.3 to 1.45.

When assessing the parameters that influence the efficiency of the dual fuel process, it is necessary to consider the impact of the amount of the pilot portion of diesel fuel injected in the cylinder. Figure 2 shows the dependencies between the reduced effective fuel consumption and the amount of the diesel fuel pilot portion for different loads and different air-fuel equivalence ratio. The diesel fuel pilot

![Figure 1. Dependence between the reduced specific fuel consumption and the air-fuel equivalence ratio (where Mk is the torque: 1 - Mk=150 N·m; 2 - Mk=350 N·m; 3 - 550 N·m)](image)

![Figure 2. Definition of optimized amounts of the diesel fuel pilot portion in percentage of the maximum supply at the full load (where $\alpha$ is the air-fuel equivalence ratio, Mk is the torque: 1 - $\alpha=1.4$, Mk=150 N·m; 2 - $\alpha=1.65$, Mk=150 N·m; 3 - $\alpha=2$, Mk=150 N·m; 4 - $\alpha=1.4$, Mk=350 N·m; 5 - $\alpha=1.65$, Mk=350 N·m; 6 - $\alpha=2$, Mk=350 N·m; 7 - $\alpha=1.4$, Mk=550 N·m; 8 - $\alpha=1.65$, Mk=550 N·m; 9 - $\alpha=2$, Mk=550 N·m.)](image)
portion was defined as a fraction of the maximum supply of diesel fuel (in diesel mode) at the given speed \(n=1200 \text{ min}^{-1}\).

As a result of these investigations a pilot portion amount within the range of 6-11 mg/cycle (5-10\%) has been defined for further tests.

The selected pilot portion has been defined based on the conditions of reaching the highest fuel efficiency. However, with such values of the cycle supply a problem of high heat density of the nozzle emerges at high loads. There are two ways to reduce the heat load at the nozzle. The first one is to increase the cycle supply of diesel fuel (in this case, the method is not applicable). The second one is to increase the injection time of the minimum amount of the cycle fuel supply. The second method may be performed by reducing the pressure in the fuel rail.

The change of the fuel rail pressure is known to have a significant influence on the jet structure of the injected fuel and its spray fineness. Consequently, when optimizing the parameters of the fuel supply in order to increase the dual-fuel process efficiency, it is necessary to consider already two factors. The first one is setting up the least pressure in the fuel rail in order to increase the time of injection and create the best conditions for the spray nozzle cooling. Moreover, the second one is maintaining the pressure above the level, at which an evidence of the working process deterioration appears.

Due to the abovementioned, the next test series have been performed in order to study the influence of the fuel rail pressure on the working process of the engine (Figure 3) operating according to the dual-fuel cycle. The tests have been performed at the engine speed \(n=1200 \text{ min}^{-1}\) at three torque levels: 135, 350 and 550 N·m, and the fuel pressure in the rail have increased from 30 to 90 MPa.

![Figure 3](image)

**Figure 3.** Dependence between the reduced specific fuel consumption and the fuel pressure in the rail (1 - \(M_k=135\) N·m; 2 - \(M_k=350\) N·m; 3 - 550 N·m)

The diagram shows that the increase of the diesel fuel pressure in the rail does not contribute to the improvement of the engine work efficiency parameters in the dual-fuel mode. Therefore, the optimized pressure may be considered as 50-60 MPa.

As a result of the optimization of the air-fuel equivalence ratio (which was calculated taking into account pilot diesel fuel and natural gas consumption), diesel fuel pilot portion and the diesel fuel pressure in the fuel rail, the settings of the control system have been adjusted and the load characteristics of the engine operating according to the dual-fuel cycle with the mixed quantitative and qualitative power control have been obtained. The load characteristic of the dual-fuel engine in certain operation mode (at the engine speed of 1200 min\(^{-1}\)) is shown in Figure 4.

The results of the performed engine experimental tests show that use of the optimized algorithms of the control of the engine working process according to the engine load characteristics ensures increase of the engine thermal efficiency by 5-8\% in certain modes in comparison to the diesel engine.
To meet the requirements of the modern standards for the emissions of harmful substances in exhaust gases, an engine should be equipped with an oxidation catalyst and selective catalytic reduction converters of nitrogen oxides (SCR). A diagram of the aftertreatment system is shown in Figure 5.

The installation of a complex aftertreatment system of exhaust gases allows refining HC, CO and NOx up to 65-88%, which ensures meeting the EURO-5 requirements by a dual-fuel engine, and after further improvement of the control and aftertreatment systems – meeting the requirements of EURO-6.

![Diagram of the complex aftertreatment system of exhaust gases SNOGMET](image)

**Figure 5.** Diagram of the complex aftertreatment system of exhaust gases SNOGMET (1 – engine controller; 2 – ambient temperature sensor; 3 – SCR supply module with controller; 4 – fluid level sensor and temperature sensor AdBlue; 5 – compressor (0.6 MPa); 6 – tank AdBlue; 7 – pressure sensor; 8 – thermostor catalytic cracking (TCC) unit; 9 – injector AdBlue (0.5 MPa); 10 – TCC unit inlet temperature sensor; 11 – TCC unit inlet pressure sensor; 12 – TCC unit outlet pressure sensor; 13 – TCC unit inlet temperature sensor; 14 – SCR catalyst module; 15 – engine; 16 – contact +24V; 17 – key; 18,19 – fuse 20 A; 20 – battery)

4. Assessment of parameters in total life cycle

For the assessment of the efficiency of use of natural gas in engines operating according to the dual-fuel cycle, the costs at all stages of the total life cycle (TLC) are assessed. The assessment has been performed according to the TLC analysis procedure for a vehicle with a powertrain, which operates using diesel fuel and according to the dual-fuel cycle.

The investigation subject was a heavy-duty vehicle with the gross weight of 23,300 kg with engine YaMZ-6566 with two versions (Table 2): diesel and dual-fuel.

For the calculations, a complex procedure for technical, economic and environmental assessment of prospects of use of alternative fuel in vehicles within the total life cycle from the raw material extraction to its use in vehicle operation and disposal, which was developed by FSUE "NAMI", has been used [18-20]. The procedure takes into consideration the consumption of natural resources and energy, emissions of hazardous substances and environmental damage caused by their negative impact, as well as money expenditures for the performance of the life cycle of alternative fuel and powertrains.
Table 2. Input data for total life cycle cost assessment

| Parameter                        | Values     |
|----------------------------------|------------|
| Price of DF, €/l                 | 0.50       |
| Price of NG, €/m³                | -          |
| Running time per service life, km| 1,000,000  |
| Annual mileage, km               | 100,000    |
| Engine price, €                  | 9182       |
| Specific DF consumption, minimum kg/kWh | 0.192 |
| Specific NG consumption, minimum kg/kWh | - |
| DF consumption per hour, kg/h    | 19.95      |
| NG consumption per hour, kg/h    | -          |
| DF consumption, l/100 km         | 30.51      |
| NG consumption, m³/100 km        | -          |

For the analysis of the dual-fuel engine economic efficiency in comparison to the diesel engine, the costs during its total life cycle and economic effect per individual components and in general have been calculated, which is shown in Table 3.

In general the positive effect of 70691 € has been obtained in comparison of the diesel engine to the engine operating according to the dual-fuel cycle. This result can be explained by lower natural gas price. Values of costs during the total life cycle on production and operation stages is shown in Figure 6.

Table 3. Total life cycle costs, €

| Fuel             | Diesel engine | Dual-fuel engine |
|------------------|---------------|------------------|
|                  | DF            | DF + NG          |
| Cumulative costs | 161741        | 91050            |
| Economic effect  | 70691         |                  |

The figure shows that the main part of expenditures, about 90%, is accounted for the operation stage.

According to the performed assessment it can be noted that use of compressed natural gas as a fuel allows reducing costs for the total life cycle almost by two times.

Carbon dioxide emissions during the vehicle total life cycle have been calculated, which is shown in Figure 7. It has been shown that dual-fuel engine allows decreasing CO₂ emissions by 22.6% in comparison to diesel variant.

Figure 6. Costs during the total life cycle of the heavy-duty vehicle with engine YaMZ-6566 operating according to the diesel and dual-fuel operation mode

Figure 7. CO₂ emissions during the total life cycle of the heavy-duty vehicle with engine YaMZ-6566 operating according to the diesel and dual-fuel operation mode
5. Conclusions
It has been found that, when converting the diesel engine YaMZ-6566 to the dual-fuel cycle operation, the minimum values of the specific effective fuel consumption are reached as follows: at the air-fuel equivalence ratio equal to 1.3...1.45, which is maintained in the engine operating modes of 10% to 100% of the full load; at the optimized value of the diesel pressure in the fuel rail – 50-60 MPa; at the amount of the diesel pilot portion equal to 6-11 mg/cycle (5-10% of the maximum fuel supply).

Use of the optimized algorithms of the control of the dual-fuel engine working process according to the engine load characteristics ensures improvement of thermal efficiency of the engine by 5-8% in certain modes (at low and medium loads) in comparison to diesel mode of operation.

As a result of the analysis of the economic efficiency of the dual-fuel engine in comparison to the diesel engine it has been found that use of natural gas as the main fuel allows reduction of costs for the total life cycle almost by two times (in Russian Federation conditions). Dual-fuel engine has total life cycle CO₂ emission by 22.6% lower than diesel one. Emission legislation requirements Euro-5 or Euro-6 for both diesel and dual-fuel modes can be fulfilled with using of complex aftertreatment system.

Therefore, the obtained results allow considering natural gas used in dual-fuel engines, as the most prospective alternative fuel in the short run.

Acknowledgments
The paper was prepared under the agreement No. 14.624.21.0005 with the Ministry of Education and Science of the Russian Federation (unique project identifier RFMEFI62414X0005) to create an experimental model of the aftertreatment system of toxic components for gas engines.

References
[1] Abedin M J, Imran A, Masjuki H H, Kalam M A, Shahir S A, Varman M and Ruhul A M 2016 An overview on comparative engine performance and emission characteristics of different techniques involved in diesel engine as dual-fuel engine operation Renewable and Sustainable Energy Reviews 60 306-316.
[2] Zhang Q, Li M and Shao S 2015 Combustion process and emissions of a heavy-duty engine fueled with directly injected natural gas and pilot diesel Applied Energy 157 217-228.
[3] Luksho V 2010 Diesel engine converting into the gas engine with a controlled thermodynamic cycle Transport on Alternative Fuel 6(18) 44-50.
[4] Wei L and Geng P 2016 A review on natural gas/diesel dual fuel combustion, emissions and performance Fuel Processing Technology 142 264-278.
[5] Roy S, Kumar D A, Banerjee R and Kumar B P 2014 A TMI based CNG dual-fuel approach to address the soot–NOₓ–BSFC trade-off characteristics of a CRDI assisted diesel engine – an EPA perspective Journal of Natural Gas Science and Engineering 20 221-240.
[6] Luksho V, Kozlov A, Terrenchenko A, Ter-Mkrtichian J and Karpukhin K 2015 Technical and economic analysis of vehicles pollutant emissions reduction technologies Biosciences Biotechnology Research Asia 12(2) 1867-72.
[7] Lukanin V and Trofimenko Yu 2001 Industrial Transport Ecology: Proc. for high schools 273.
[8] Yang B, Xi C, Wei X, Zeng K and Lai M 2015 Parametric investigation of natural gas port injection and diesel pilot injection on the combustion and emissions of a turbocharged common rail dual-fuel engine at low load Applied Energy 143 130-137.
[9] Luksho V and Mironov M 2010 Economic efficiency of use of natural gas as a motor fuel in vehicles with diesel power plants Transport on Alternative Fuel 2(14) 20-26.
[10] Loumici M S, Loubar K, Tarabe L, Balistrour M, Niculescu D-C and Tazerout M 2014 Towards improvement of natural gas-diesel dual fuel mode: An experimental investigation on performance and exhaust emissions Energy 64 200-211.
[11] Wang Z, Zhao Z, Wang D, Tan M, Han Y, Liu Z and Dou H 2016a Impact of pilot diesel ignition mode on combustion and emissions characteristics of a diesel/natural gas dual fuel heavy-duty engine Fuel 167 248-256.
[12] Panchishny V, Luksho V, Kozlov A, Terenchenko A and Karpukhin K 2015 The problem of toxicity of gas engines and their solutions *Biosciences Biotechnology Research Asia* **12** (Spl. Edn. 2) 217-224.

[13] Lim O, Iida N, Cho G and Narankhuu J 2012 The research about engine optimization and emission characteristic of dual fuel engine fueled with natural gas and diesel *SAE* 2012-32-0008.

[14] Yang B, Wei X, Xi C, Liu Y, Zeng K and Lai M-C 2014 Experimental study of the effects of natural gas injection timing on the combustion performance and emissions of a turbocharged common rail dual-fuel engine *Energy Conversion and Management* **87** 297-304.

[15] Li W, Liu Z and Wang Z 2016 Experimental and theoretical analysis of the combustion process at low loads of a diesel natural gas dual-fuel engine *Energy* **94** 728-741.

[16] Wang B, Li T, Ge L and Ogawa H 2016b Optimization of combustion chamber geometry for natural gas engines with diesel micro-pilot-induced ignition *Energy Conversion and Management* **122** 552-563.

[17] Cameretti M C, Tuccillo R, De Simio L, Iannaccone S and Ciaravola U 2016 A numerical and experimental study of dual fuel diesel engine for different injection timings *Applied Thermal Engineering* **101** 630-638.

[18] Zvonov V, Kozlov A and Kutenev V 2001 Environmental Safety of the Cars in the Full Life Cycle 248.

[19] Luksho V, Kozlov A and Terenchenko A 2011 Total life cycle assessment of natural gas as motor fuel *Transport on Alternative Fuel* **3(21)** 4-9.

[20] Vershkov L, Groshev V, Gavrilov V et al 1999 Temporary methods of definition of the prevented ecological damage 68.