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INCREASE IN THE FUEL EFFICIENCY OF A DIESEL ENGINE BY DISCONNECTING SOME OF ITS CYLINDERS

Alexander Gritsenko[1,2], Vladimir Shepelev[2], Semen Fedoseev[3], Tatyana Bedych[4]

[1]Department of Automobile Transport, South Ural State University, Chelyabinsk, Russia
[2]Department of Engineering and Technology, South Ural State Agrarian University, Chelyabinsk, Russia
[3]Military-air Academy named after Professor N. E. Zhukovsky and Y. A. Gagarin, Chelyabinsk, Russia
[4]M. Dulatov Kostanay Engineering and Economic University, Kostanay, Kazakhstan

Abstract. *In fuel economy, a rising level of interest in heavy duty diesel engines that industry has witnessed over the last few years continues to go up and this is not likely to change. Lowering the fuel consumption of all internal combustion engines remains a priority for years to come, driven by economic, legislative, and environmental reasons. According to statistics, the share of operating expenses to ensure transport operations in industrial production is 15-20%, wherein 16-30% of the total volume of transport operations concerns a car, tractor, and trailer. During transport operations, the engine load by the torque, in most cases, does not exceed 40-50%. The paper investigates the increase in fuel efficiency of cars and tractors by disconnecting some of the engine cylinders operated in low-load and idling modes. The research has led to the establishment of the theoretical dependencies between the effective power, engine efficiency, mass of the transported cargo, speed of the car (tractor) and the number of disconnected engine cylinders. Results of experiments suggest the interdependencies of the performance parameters of the car (tractor) when disconnecting some of the engine cylinders. It has also been established that the maximum reduction in the hourly fuel consumption occurs in the idling mode while it decreases along with an increase in the load.*

Key Words: *Engine, Fuel Shutoff, Efficiency, Environmental Friendliness, Control*

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Corresponding author: Vladimir Shepelev
Affiliation, Department of Automobile Transport, South Ural State University, 76, Lenin Prospect, 454080 Chelyabinsk, Russia
E-mail: shepelevvd@susu.ru

1. INTRODUCTION

The objective of current research on internal combustion engines is to further reduce exhaust emissions while simultaneously reducing fuel consumption [1]. The issues of increasing the fuel efficiency of cars and tractors by disconnecting some of engine cylinders have not been sufficiently studied despite a significant number of publications dealing with this topic [2-9].

Patrahaltsev et al. [2] carried out the comparison of opportunities to raise the diesel economy during some testing cycles by disconnecting some cylinders or cycles. It has been established that during reduction of the loading coefficient from 0.6 to 0.36, the rising of economy changes from 3.1 to 7.2%.

Liu and Kuznetsov [3] determined that the valve system in deactivated cylinders has a significant effect on the specific fuel consumption. Authors investigated the engine performance in partial load modes at different rotational speeds and torques and with a varying number of deactivated cylinders. The obtained results demonstrate the characteristics of the engine working process under cylinder deactivation and enable a more accurate estimation of the effect of this engine control method.

Berdnikov et al. [4] proposed a method of forming the order of disconnection of the cylinders of the engine in order to obtain the necessary engine power for an efficient and economical operation of the engine.

Gosala et al. [5] demonstrated that it is possible to operate a diesel engine at low loads in cylinder deactivation without compromising its transient torque/power capabilities, a key finding in enabling the practical implementation of cylinder deactivation in diesel engines.

Mo et al. [6] presented results which show that, when the mean effective pressure of the engine is lower than 3.5 bar, cylinder deactivation decreases the brake specific fuel consumption by 0-17% and by 26% at idle if the intake valves and the exhaust valves are kept closed at the same time. However, the engine and the supercharger do not match well after deactivation and the mass of intake air decreased greatly, which also resulted in a large decrease in the nitrogen oxide emissions.

Thees et al. [7] implemented a new cylinder activation concept (“3/4-cylinder concept”) with the aim of reducing fuel consumption. A fully variable valve train was developed for this engine, which both improves the functionality of the 3/4-cylinder concept and can have a positive influence on exhaust emissions through internal exhaust gas re-circulation. A comparison of this engine concept with its series reference based on measurement data showed a fuel economy advantage of up to 5.2% in the low load field cycles of the DLG PowerMix. The maximum fuel consumption benefit in the low load engine regime exceeded 15% in some of the operating points.

Vinodh et al. [8] deals with maintaining the efficiency of the engine at different loading conditions. In this paper a 6-cylinder engine is converted into a 4-cylinder engine. For this, the crankshaft is divided into several segments, so that it will be possible to disengage two of the cylinders from the other four cylinders. During this conversion, servo motor is used to vary the crank angle according to the number of cylinders, which in turn is controlled by ECU (Electronic Control Unit). The engine will be operated at its maximum efficiency.

Pillai et al. [9] established that the modified baseline model that includes cylinder deactivation maintains comparable emission levels through the optimization of exhaust gas recirculation and variable geometry turbocharger. The results demonstrated reductions in brake specific fuel consumption and higher exhaust gas temperatures for low and part load operating points. Disabling fuel injectors and the valve train on half of the engine's cylinders allowed for the implementation of cylinder deactivation. Lower engine pumping work and reduced heat transfer to the cylinder walls resulted in reduced fuel consumption.

The works of scientists [10-15] deal with complex issues of a more complete additional loading of the cylinders remaining in operation, a decrease in specific and liter fuel consumption, and an increase in fuel efficiency.

The studies carried out by the above authors deal with the issues of increasing the fuel efficiency of engines by fuel shutoff in the idling ICE cylinders. But the sources do not provide methods for the analytical calculation of the fuel efficiency of cars and tractors during transport operations when some of the engine cylinders are off [16-19].

The strengths and weaknesses of the methods used are summarized in the Table 1.

Table 1 The strengths and weaknesses of the used methods

Deactivation method	Strengths	Weaknesses
Fuel-off with exhaust gas transfer [20-24]	Preservation of the thermal conditions of the cylinders	High costs to change the vehicle configuration
Fuel-off without exhaust gas transfer [25-28]	No need for reconstruction costs	Change in the thermal conditions of the deactivated cylinders
Disconnection of the drive of the gas distribution mechanism [29]	No gas exchange losses	Violation of the thermal conditions of the deactivated cylinders
a) valves closed	-	Uneven wear of the deactivated cylinders
b) valves open	-	Increase in the toxicity of exhaust gases after reactivation
c) exhaust gas transfer from the working cylinders through the deactivated cylinders	-	Problems with the accumulation of lubricating oil in the deactivated cylinders
d) circulation of gases in the deactivated cylinders from the outlet to the inlet	-	Increased design features
Deactivation of pistons [23, 24]	No mechanical losses	Increased noise and vibration, disbalancing
a) breaking of the rigid connection between the crankshaft and the piston	No major structural changes needed	Complicated maintenance and repair

Knowing that the prices of hydrocarbon fuels in Russia (despite a decrease in the global prices) are constantly growing, and the rated power of tractor engines sustains the upward trend, the topic of the work aimed at increasing the fuel efficiency of cars and tractors is relevant.

2. Theoretical Research

Disconnection of several engine cylinders is advisable when the car (tractor) moves in the transport mode with a small load along a horizontal supporting surface (a road with asphalt concrete or improved surfacing), as well as downhill [30-32].

During the tests, we used a KI-5543 run-in and test stand. The structural diagram of the stand is shown in Fig. 1. The loading device of the stand allows us to load the ICE with a maximum torque of 400 Nm and the range of ICE crankshaft speeds of – 1,000÷3,200 rpm.

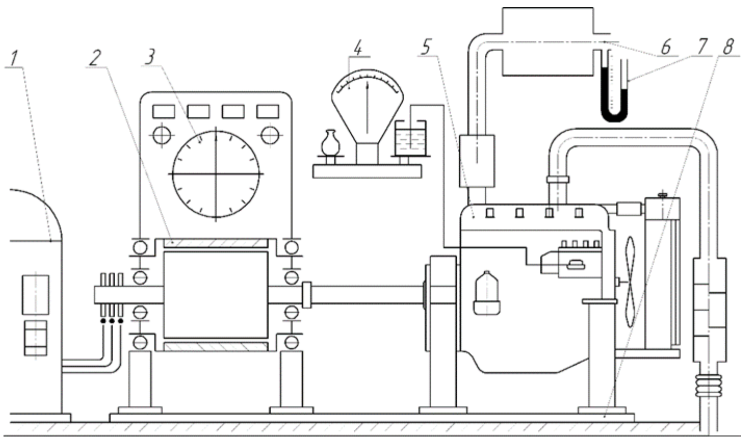


Fig. 1 A simplified diagram of the test bench with D-240 (1 – regulator for the ICE loading; 2 – balancing mechanism; 3 – torque meter; 4 – weighting device to control fuel consumption; 5 – D-240 engine; 6 – diffuser; 7 – U-shaped manometer; 8 – stand base)

We installed two solenoid valves in the fuel system of the D-240 engine to prepare for the tests (Fig. 2). Two solenoid valves are installed on the fuel system shown in Fig. 2. The solenoid valves allow us to deactivate the working cylinders of the ICE in real time. When the ICE cylinders are off, the incoming fuel is drained back into the fuel tank. The drive of the gas distribution mechanism was deactivated by removing the pushers, after which the inlet and outlet valves of the deactivated cylinders were closed.

To perform calculations, we made the following assumptions: we consider the transmission efficiency to be constant at each of the actual gears; a car (tractor) is moving at a constant speed (V_m=const), uniformly (j=0), on a horizontal surface (α=0º), without longitudinal vibrations affecting the changes in the tractive effort and torque of the engine, without slipping (δ= 0); we neglect aerodynamic drag force P_w because of the low movement speed in the case of a tractor [33-37].

Fig. 2 Fuel system of the D-240 engine with solenoid valves to turn off the fuel supply of two ICE cylinders

Taking into account the accepted assumptions, the engine load factor by the torque (K_l) is determined by the expression [16, 18]:

$$K_l = \frac{M_e}{M_{en}} = \left(G_{trac} \cdot f_{trac} + G_{trail} \cdot f_{trail}\right) \frac{R_w \cdot 10^3}{\eta_t \cdot i_t \cdot M_{en}} \qquad (1)$$

where M_e is current engine torque, Nm; M_{en} is the engine torque at the nominal power, Nm; G_{trac} is the weight of the car (tractor) with the load (or without load), t; G_{trail} is the weight of the trailer with load (or without load), t; f_{trac}, f trail is the coefficient of the rolling resistance of the car (tractor) and trailer; R_w is the dynamic radius of the drive wheels of the car (tractor), m; i_t is the transmission number; η_t is the mechanical transmission efficiency for the selected gear.

The degree of the variation of engine crankshaft speed (k_n) depends on actual movement speed (V_m) of the car (tractor), the transmission number, the dynamic radius of the drive wheels, and the nominal speed of engine crankshaft (n_n):

$$k_n = \frac{n}{n_n} = \frac{V_m \cdot i_t}{0.05 \cdot R_w \cdot n_n} \qquad (2)$$

where n is current engine crankshaft speed, rpm.

When choosing the main estimated indicator characterizing the fuel efficiency level, we took into account that the economic effect when disconnecting some of the engine cylinders takes place only at low loads (while the specific effective fuel consumption has overestimated values, which are not exponential). Thus, the hourly fuel consumption is adopted in this work as the main estimated indicator affecting the fuel efficiency of a car (tractor). The function of the dependence of hourly fuel consumption Gf on the engine operating mode, which changes when some of its cylinders are off, can be analytically presented as follows:

$$G_f = k_n \frac{0.12 \cdot n_n}{H_u \cdot \eta_i} \left(K_l \frac{3M_{en}}{955} + p_{ml} \frac{V_h}{\tau} z_w \right) \quad (3)$$

where H_u is the lower calorific value, MJ/kg; η_i is the indicated efficiency; p_{ml} is the average pressure of mechanical losses, Pa kW; V_h is the engine volume, l; z_w is the number of working cylinders; τ is the engine cycle.

An analysis of the above dependencies shows that the car (tractor) engine fuel consumption is affected by the engine operating mode determined by the degree of the variation on the crankshaft speed, the indicated efficiency, the engine load factor by the torque, as well as the number of working cylinders and the nominal average pressure of mechanical losses.

To this end, we should establish regularities of changes in these parameters when performing transport operations, as well as when disconnecting some of the engine cylinders.

To solve these problems, we calculated the weighted average values of the engine load factors at n=const for transport transmissions; then, we aligned these values with the operating modes of the transport-tractor unit (TTU): 1) engine idling K_l=0; 2) tractor idling: 0>K_l>0.14; 3) TTU idling: 0.14≥K_l>0.211; 4) TTU operating mode: K_l≥ 0.211.

When disconnecting the cylinders to maintain the required engine operating mode, the remaining working cylinders should be supplied with a larger amount of fuel at an increased cyclical supply, consequently, the indicated pressure increases in them. When the engine load changes, the fuel combustion quality characterized by the indicated efficiency is adequately described by the equation of the quadratic parabola depending on the indicated pressure:

$$\eta_i = A \cdot p_i^2 + B \cdot p_i + C \quad (4)$$

where A, B, C are the coefficients; p_i is the average indicated pressure in the cylinder, MPa.

This dependence was obtained in the course of the analysis of the load characteristics of the engine at a constant speed, as well as the thermal calculation of the engine for different load conditions. In our work, we found the following empirical coefficients for the four-cylinder D-240 engine: A = –0.872; B = 0.953; C = 0.256.

To determine the change in mechanical losses when the cylinder is off, which are usually characterized by mechanical efficiency, we introduced the coefficient of variation of mechanical losses k_m of the engine when some of the cylinders are off:

$$k_m = \frac{N_{ml\_Zp}}{N_{ml\_i}} \quad (5)$$

where N_{ml_Zp} is the power of mechanical losses when some cylinders are on, kW; N_{ml_i} is the power of mechanical losses when all i cylinders are on, kW.

Fig. 3 shows the dependence of the change in k_m on the number of working cylinders calculated for a four-cylinder engine when using two ways of disconnecting cylinders.

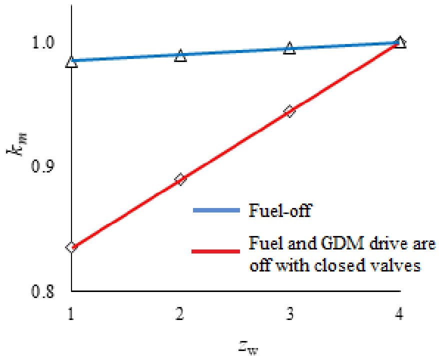


Fig. 3 The dependence of the coefficient of the power of mechanical losses variation on the number of working cylinders of a 4-cylinder ICE

The ratio of the nominal effective engine power when some of the cylinders are off to the nominal effective engine power when all the cylinders are on is denoted as the coefficient of the nominal effective power variation when some of the cylinders are off k_N:

$$k_N = \frac{N_{e\_Zp\max}}{N_{e\_i\max}} = \frac{z_p}{i \cdot \eta_{m\_i\max}} - k_m\left(\frac{1}{\eta_{m\_i\max}} - 1\right) \tag{6}$$

Having calculated the values of this coefficient for different ways to disconnect the cylinders by the example of a 4-cylinder engine, we obtain dependencies of k_N on the number of working cylinders (Fig. 4).

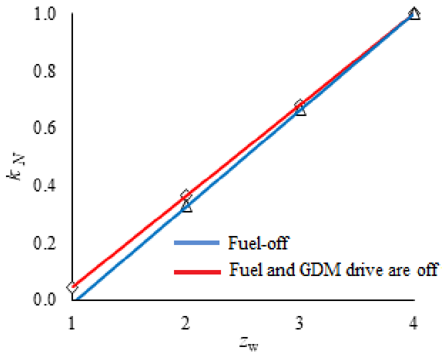


Fig. 4 The dependence of the coefficient of maximum effective power variation on the number of working cylinders of a 4-cylinder ICE

We can see from the dependency graph shown in Fig. 5 that when the fuel and valves are off, the engine will develop a larger power than if only the fuel supply is off.

Fig. 5 shows the dependence of the change in the hourly fuel consumption calculated for the D-240 engine with a different number of working cylinders on the engine load factor.

Consumption lines for different numbers of working cylinders have intersection points, conventionally called “zero-economy points”. The engine load factor at these points is such that the fuel consumption is identical both when all the cylinders are on and when some of the cylinders are off.

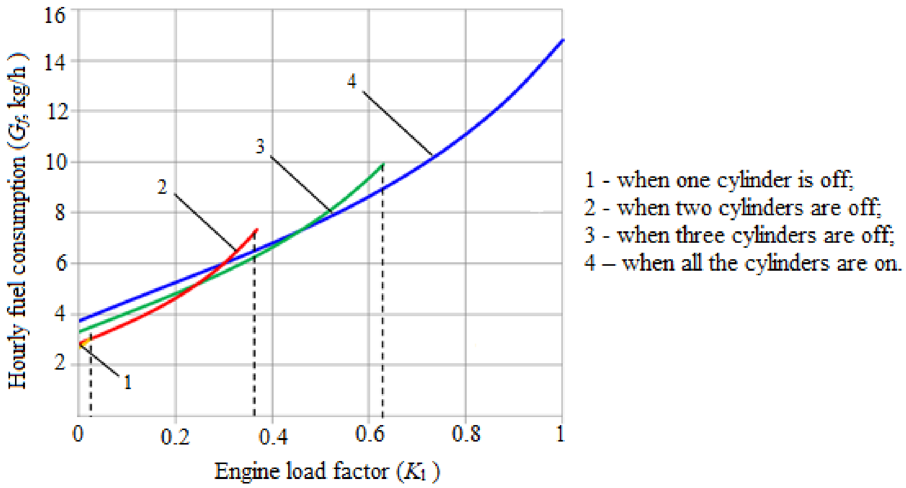


Fig. 5 The estimated dependences of the fuel consumption of the D-240 engine on the load factor at a different number of working cylinders (*n*=2,200 rpm)

An analysis of the presented dependencies shows that when the engine is loaded less than at the zero-economy points, the fuel consumption is higher when all the cylinders are on than when one or several cylinders are off, so it is advisable to disconnect the engine cylinders. In case of a larger load, the fuel consumption is higher when the cylinders are off than when the cylinders are on, so it is not advisable to disconnect the cylinders.

The maximum value of decreasing the hourly fuel consumption ΔG_f:

$$\Delta G_f = G_{f\_i} - G_{f\_Zw} \tag{7}$$

where G_{f_i} is the hourly fuel consumption when all the cylinders are on, kg/h; G_{f_Zw} is the hourly fuel consumption when some of the cylinders are off, kg/h, which corresponds to the maximum economy, at K_l=0 (engine idling mode), while at K_l=0.32, ΔG_f=0. With a further increase in the engine load, the fuel consumption further grows to a certain value K_l=k_N, above which the engine does not work at a given frequency and with a given number of working cylinders.

The dependence of the decrease in the hourly fuel consumption ΔG_f calculated for the D-240 diesel engine depending on the engine load factor K_l is shown in Fig. 5.

In Fig. 6 the dashed lines show the engine load levels “XX_Tp” – when the car (tractor) is moving without a trailer, “XX_TTU” – when the car (tractor) is moving with an empty trailer. In these modes, the expected fuel economy is: when two cylinders are on - 7%, when three cylinders are on - 4% (for XX_TTU) and when two cylinders are on - 12%, when three cylinders are on - 5% (for XX_Tp). Obviously, to ensure the minimum fuel consumption, the engine should operate according to the *ABCD* curve with a cut-off, depending on the engine load and the corresponding number of cylinders. The calculation results are summarized in Table 2.

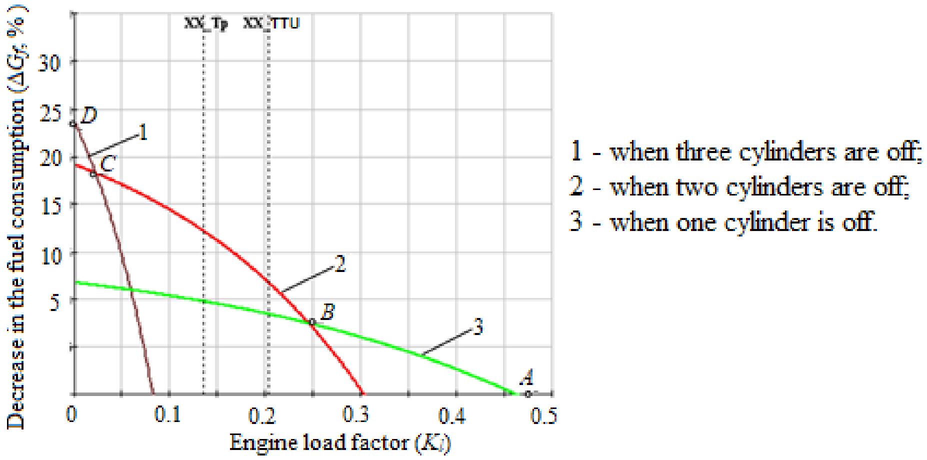


Fig. 6 The estimated dependences of the decrease in the fuel consumption ΔG_f of the D-240 engine on load factor K_l when a different number of cylinders is on (n=2,200 rpm)

For different car (tractor) operating modes, we calculated the traction and power indicators and the decrease in the fuel consumption, based on which we selected the optimal number of cylinders to be disconnected.

Table 2 The results of calculating the parameters of the car (tractor) with disconnecting two engine cylinders, during standing and moving in the transport mode on an unsurfaced road

Parameter	Engine idling	Tractor idling	TTU idling	TTU operating mode
Load factor K_l	0	0.138	0.211	0.370
Cargo mass m_{car}, kg	0	0	0	4000
Traction resistance, *R*, kN	0	0	0.68	2.28
Effective engine power *Ne*, kW	0	7.66	11.52	20.61
Decrease in the hourly fuel consumption ΔG_f, kg/h	1.08	0.82	0.62	0.25
consumption ΔG_f, %	28.67	17.1	11.64	3.88
Number of working cylinders, z_w	1	2	2	2

Thus, we found the desired analytical and graphical dependencies of the fuel consumption on the engine load and the number of working cylinders when the fuel supply and the GDM drive are off, based on which we determined a rational number of cylinders to be disconnected for various operating modes of the car (tractor).

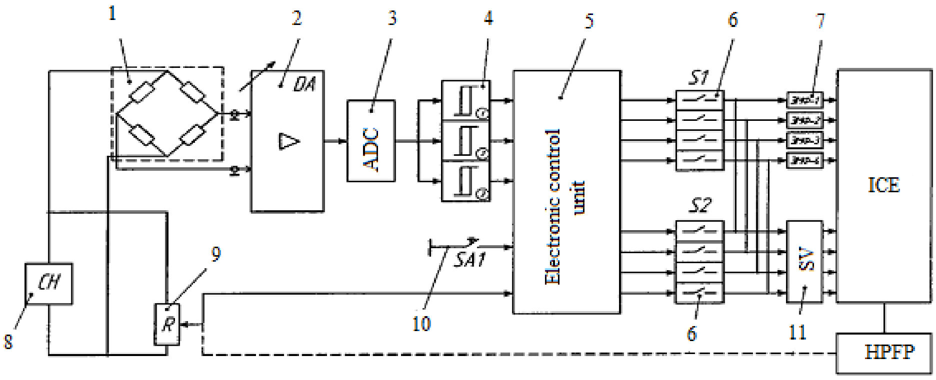
3. Experimental Research Procedure

The experimental research program included: 1. Preparation of control instruments, recording instruments, and equipment for bench and field tests; 2. Development of experimental research methods.

The experimental research was carried out in two stages: 1. bench tests of the D-240 diesel engine in laboratory conditions; 2. field tests during the operation of the car (tractor) during three engine operation variants: a) All cylinders are on; b) Only the fuel supply is off; c) The fuel supply and the GMD drive (valves in the closed position) are off.

During the field tests of the car (tractor), the cylinder disconnection process was controlled through an updated spring-loaded tow bar mounted in the hitch bar of the trailer and equipped with limit switches activated at certain traction resistance values. We used an electronic control signal damper to eliminate false alarms at an oscillation frequency of the traction resistance of over 1 Hz.

Fig. 7 shows a developed block diagram of an automatic engine operation control unit taking into account the load.



1 – strain segment with strain gauges; 2 – strain booster; 3 – analog-to-digital converter;
4 – three-level comparator; 5 – electronic control unit; 6 – four-channel power keys; 7 – nozzles;
8 – voltage stabilizer; 9 – slide-wire gauge linked with the fuel control unit; 10 – fuel shutoff key;
11 – solenoid valves.

Fig. 7 Diagram of an automatic engine operation control unit taking into account the load of the transport unit

To reduce the number of experiments while maintaining sufficient accuracy and reliability of the results, we carried out the experimental research ac-cording to the plan based on the theory of experimental design and the experience accumulated during similar works. The basis of the experimental research plan is a three-level Box-Benkin second-order design.

4. Results of the Experimental Research

When the engine operates according to the load characteristic (Fig. 8) at a constant engine crankshaft speed, it is necessary to ensure the specified engine load value for all variants of its operation.

The change in the engine performance (cyclic fuel supply, hourly fuel consumption, actual air flow, excess air ratio, coefficient of admission, temperature of exhaust gases, indicated efficiency, specific indicated fuel consumption) is explained by the same causes, as during idling. However, the energy of the used fuel is consumed, in contrast to the changes in the engine mechanical losses (proportional to the crankshaft speed), to overcome the moment of resistance and to realize the effective power. The power of the D-240 engine is limited to 33 kW because at a higher load, the economic effect is not observed when the cylinders are off. When two cylinders of the D-240 engine are off, the power of mechanical losses at the rated frequency decreases by 11%. During idling, when the fuel supply and the GDM drive of the second and third cylinders are off, the hourly consumption rate at the nominal crankshaft speed is reduced by 24.4%. When the D-240 engine is running under load at the nominal speed: a) when only the fuel supply is off, at a load from 0 to 8% of the nominal value, the fuel economy decreases from 8% to 0%; b) when the fuel and the valves of a half of the cylinders are off with an increase in the load from 0 to 39%, the fuel economy decreases from 24.4% to 0%.

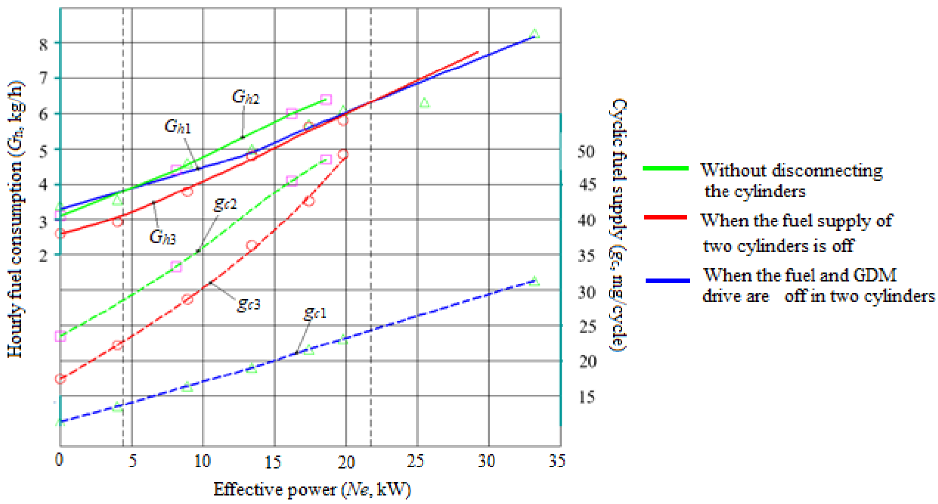


Fig. 8 Load characteristics of the D-240 engine (n=2,200 rpm)

The value of the maximum engine power when working on two cylinders and at a nominal speed is 37–39%. The results of the design and experimental studies of the D-240 engine of the MTZ-82 tractor during field tests are compared in Fig. 9.

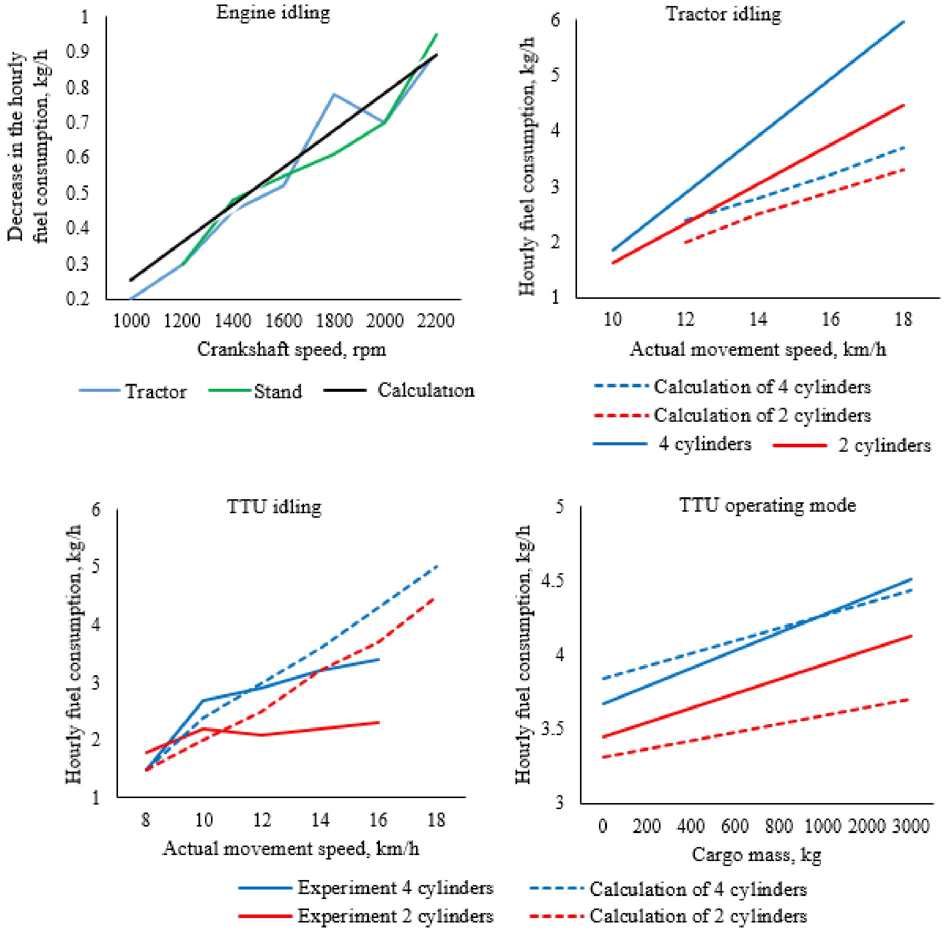


Fig. 9 The dependencies of the hourly fuel consumption on the operating conditions of the car (tractor)

The analysis of the theoretical and experimental dependences allows us to conclude that the fuel efficiency of TTUs can be improved when operating with a low engine torque load characteristic of transport operations. This can be achieved by increasing the load of some engine cylinders while deactivating other cylinders. It is assumed that an increase in the efficiency of fuel combustion in working cylinders and a decrease in mechanical losses of the engine in deactivated cylinders will allow us to reduce the total fuel consumption, which, in turn, will lead to a decrease in specific energy consumption for the implementation of the transport process. This is particularly relevant with regard to the optimization model for:

- the relationship between the effective power, the engine economy, the weight of the transported cargo, the speed of the TTUs, and the number of deactivated ICE cylinders;

- the relationship between the energy and fuel-economic performance of the TTUs and the engine of the transport tractor in different modes during transport operations.

For one of the options of a device for disconnecting some of the cylinders, we calculated the cost of re-equipping the MTZ-82 tractor for operation in the economy mode, which comprised 53 thousand rubles. Based on the statistical data, we calculated the TTU engine operating time in the modes ensuring fuel efficiency. The payback period of the device for disconnecting some of the engine cylinders is 2.3 years. The annual economic effect of the introduction of the research results and the developed devices is 21 thousand rubles per one MTZ-80/82 tractor.

5. Conclusions

An increase in the fuel efficiency of the tractor and transport unit operating under a low engine load by the torque, which is typical of transport operations, can be achieved by increasing the load of several engine cylinders of a transport tractor at a simultaneous disconnection of other ICE cylinders. Based on the established regularities of changes in the engine performance: the power of mechanical losses, the effective power, and hourly fuel consumption depending on the number of working cylinders, we developed a mathematical model for the operation of a car (tractor) engine when some of its cylinders are off, which allows us to determine analytically with sufficient reliability the rational number of working engine cylinders and fuel consumption depending on the values of traction effort, traction power, the mass of the transported cargo in various operating modes and road operating conditions of the car (tractor).

We established that when performing transport operations of a car (tractor) as part of the MTZ-80/82 transport tractor and 2PTS-4 trailer, it is expedient to disconnect one or two engine cylinders. In this case, fuel consumption depends on the ICE load determined by the road conditions, the transmission number, and the degree of the trailer loading. So, when the car (tractor) moves in the eighth speed position of the gearbox at a speed of 18.5 km/h along an unsurfaced traffic-compacted road, the disconnection of two engine cylinders (by turning off the fuel supply and the GDM drive) allows us to reduce the fuel consumption when the tractor moves without a trailer by 17.1 %; when the car (tractor) moves without cargo - by 11.6%; in the “zero-economy point” operating mode it corresponds to the mass of the transported cargo of 2.45 tons.

The annual effect of the introduction of the research results and the developed devices expressed in monetary terms is 21 thousand rubles per one MTZ-80/82 tractor.

References

1. Shatrov, M.G., Sinyavski, V.V., Dunin, A.Y., Shishlov, I.G., Vakulenko, A.V, 2017, *Method of conversion of high- and middle-speed diesel engines into gas diesel engines*, Facta Universitatis-Series Mechanical Engineering, 15(3), pp. 383-395.
2. Patrakhaltsev, N.N., Kamyshnikov, R.O., Anoshina, T.S., Skripnik, D.S., 2014, *Regulation of the yamz-238 diesel engine by turning off the cylinders under different operating modes*, Construction and road vehicles, 9, pp. 28-31.
3. Liu, Y., Kuznetsov, A.G., 2019, *An analysis of the working process of a diesel engine under cylinder deactivation*, BMSTU Journal of Mechanical Engineering, 11(716), pp. 9-18.

4. Berdnikov, A.A., Mingazov, S.R., Zhukov, A.A., 2017, *Improving economic performance of the internal combustion engine by switching off of the cylinders*, Modern high technologies, 1, pp. 12-16.
5. Gosala, D.B., Allen, C.M., Ramesh, A.K., Shaver, G.M., McCarthy, J., Stretch, D., Koeberlein, E., Farrell, L., 2017, *Cylinder deactivation during dynamic diesel engine operation*, International Journal of Engine Research, 18(10), pp. 991-1004.
6. Mo, H., Huang, Y., Mao, X., Zhuo, B., 2014, *The effect of cylinder deactivation on the performance of a diesel engine, Proceedings of the Institution of Mechanical Engineers*, Part D: Journal of Automobile Engineering, 228(2), pp. 199-205.
7. Thees, M., Buitkamp, T., Guenthner, M., Pickel, P., 2020, *High efficiency diesel engine concept with variable valve train and cylinder deactivation for integration into a tractor*, Proc. ASME 2019 Internal Combustion Engine Division Fall Technical Conference, ICEF 2019, Chicago.
8. Vinodh, B., 2005, *Technology for cylinder deactivation*, Proc. SAE World, Detroit.
9. Pillai, S., Lorusso, J., Van Benschoten, M., 2015, *Analytical and experimental evaluation of cylinder deactivation on a diesel engine, Proc. SAE Commercial Vehicle Engineering Congress*, COMVEC 2015, Donald E. Stephens Convention Center Rosemont.
10. Galindo, J., Dolz, V., Monsalve-Serrano, J., Bernal Maldonado, M.A., Odillard, L., 2021, EGR cylinder deactivation strategy to accelerate the warm-up and restart processes in a Diesel engine operating at cold conditions, International Journal of Engine Research, doi: 10.1177/14680874211039587
11. Fridrichová, K., Drápal, L., Vopařil, J., Dlugoš, J., 2021, *Overview of the potential and limitations of cylinder deactivation*, Renewable and Sustainable Energy Reviews, 146, 111196.
12. Tunçer, E., Sandalcı, T., Karagöz, Y., 2021, *Investigation of cycle skipping methods in an engine converted to positive ignition natural gas engine*, Advances in Mechanical Engineering, 13(9), doi: 10.1177/16878140211045454
13. Tunçer, E., Sandalci, T., Pusat, S., Balcı, Ö., Karagöz, Y., 2021, *Cycle-skipping strategy with intake air cut off for natural gas fueled Si engine*, Science Progress, 104(3), doi: 10.1177/00368504211031074
14. Omanovic, A., Zsiga, N., Soltic, P., Onder, C., 2021, *Increased internal combustion engine efficiency with optimized valve timings in extended stroke operation*, Energies, 14(10), 2750.
15. Gößnitzer, C., Givler, S., 2021, *A new method to determine the impact of individual field quantities on cycle-to-cycle variations in a spark-ignited gas engine*, Energies, 14(14), 4136.
16. Gritsenko, A.V., Shepelev, V.D., Moor, A.D., 2020, *A test method for individual control of the engine's ecological parameters*, Proc. International Science and Technology Conference on Earth Science, ISTCEarthScience 2019, Russky Island, 459(4).
17. Zammit, J.-P., McGhee, M.J., Shayler, P.J., Pegg, I., 2014, *The influence of cylinder deactivation on the emissions and fuel economy of a four-cylinder direct-injection diesel engine*, Proc. Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 228(2), pp. 206-217.
18. Gritsenko, A.V., Glemba, K.V., Petelin, A.A., 2019, *A study of the environmental qualities of diesel engines and their efficiency when a portion of their cylinders are deactivated in small-load modes,* Journal of King Saud University - Engineering Sciences, 33(1), pp. 70-79.
19. Scassa, M., Körfer, T., Chen, S.K., Fuerst, J., Younkins, M., Nencioni, M., George, S., 2019, *Smart cylinder deactivation strategies to improve fuel economy and pollutant emissions for diesel-powered applications*, SAE Technical Papers, 2019-September, doi: 10.4271/2019-24-0055
20. Makushev Yu. P., Drevel A. V., Makusheva T. A., 2015, *A methodology for calculating, diagnosing, and regulating the gas transfer system of the engine supercharger*, Bulletin of the Siberian State Automobile and Highway Academy, 3(43), pp. 20-25.
21. Erokhov, V.I., 2013, *Waste gas recirculation system of modern engines*, Alternative Fuel Transport, 4(34), pp. 36-42.
22. Erokhov, V.I., 2017, *Toxicity of modern vehicles (methods and means of reducing harmful atmospheric emissions)*, Moscow. Forum Publishing House.
23. Matsulevich, M. A., Lazarev, E.A., 2013, *Parameters of the combustion process and indicators of the working cycle of a gasoline engine with intermediate cooling of recirculated exhaust gases*, Bulletin of South Ural State University. Series: Mechanical Engineering, 13(1), pp. 127-131.
24. Matsulevich, M. A., Lazarev, E.A., 2012, *A mathematical model of the working cycle of a gasoline engine with exhaust gas recirculation*, Bulletin of South Ural State University. Series: Mechanical Engineering, 33(292), pp. 60-64.
25. Bashirov, R.M., Galiullin, R.R., 2008, *Basic characteristics of the fuel system of a tractor diesel engine with fuel-off*, Mechanization and Electrification of Agriculture, 11, pp. 46–47.

26. Bashirov, R.M., Safin, F.R., Magafurov, R.Zh., 2017, *The improvement of the method for regulating diesel fuel equipment*, Bulletin of Altai State Agrarian University, 6(152), pp. 158-163.
27. Patrahaltsev, N.N., Strashnov, S.V., Melnik, I.S., Kornev, B.A., 2012, *Regulation of a diesel engine by changing its working volume*, Tractors and Agricultural Machinery, 2, pp. 19–22.
28. Patrakhaltsev, N. N., Vinogradov, L. V., Lotfullin, Sh. R., 2017, *Improving the efficiency of the KAMAZ gas engine by the deactivation of some cylinders at low load modes*, Alternative Fuel Transport, 1(55), pp. 31-35.
29. Chudakov, D. A., 1972, *Fundamentals of the theory and calculation of a tractor and a vehicle*, Moscow: Kolos, 384 p.
30. Yang, J., Quan, L., Yang, Y., 2012, *Excavator energy-saving efficiency based on diesel engine cylinder deactivation technology*, Chinese Journal of Mechanical Engineering (English Edition), 25(5), pp. 897-904.
31. Boretti, A., Scalzo, J., 2013, *A novel mechanism for piston deactivation improving the part load performances of multi cylinder engines*, Proc. FISITA 2012 World Automotive Congress, Lecture Notes in Electrical Engineering, Beijing, 189 LNEE (VOL. 1), pp. 3-17.
32. Joshi, M., Gosala, D., Allen, C., Srinivasan, S., Ramesh, A., Vanvoorhis, M., Taylor, A., Vos, K., Shaver, G., McCarthy, J., Jr., Farrell, L., Koeberlein, E.D., 2018, *Diesel engine cylinder deactivation for improved system performance over transient real-world drive cycles*, Proc. 2018 SAE World Congress Experience, WCX 2018, Cobo CenterDetroit.
33. Ramesh, A.K., Gosala, D.B., Allen, C., Joshi, M., McCarthy, J., Jr., Farrell, L., Koeberlein, E.D., Shaver, G., 2018, *Cylinder deactivation for increased engine efficiency and aftertreatment thermal management in diesel engines*, Proc.2018 SAE World Congress Experience, WCX 2018, Cobo Center Detroit.
34. Ramesh, A.K., Shaver, G.M., Allen, C.M., Nayyar, S., Gosala, D.B., Caicedo Parra, D., Koeberlein, E., McCarthy, J., Nielsen, D., 2017, *Utilizing low airflow strategies, including cylinder deactivation, to improve fuel efficiency and after treatment thermal management*, International Journal of Engine Research, 18(10), pp. 1005-1016.
35. Gosala, D.B., Allen, C.M., Shaver, G.M., Farrell, L., Koeberlein, E., Franke, B., Stretch, D., McCarthy, J., Jr., 2019, *Dynamic cylinder activation in diesel engines*, International Journal of Engine Research, 20(8-9), pp. 849-861.
36. Gritsenko, A., Shepelev, V., Zadorozhnaya, E., Shubenkova, K., 2020, *Test diagnostics of engine systems in passenger cars*, FME Transactions, 48(1), pp. 46-52.
37. Sinyavski, V., Shatrov, M., Kremnev, V., Pronchenko, G., 2020, *Forecasting of a boosted locomotive gas diesel engine parameters with one- and two-stage charging systems*, Reports in Mechanical Engineering, 1(1), pp.192-198.