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Method for Calculating Carbon Dioxide Emissions of Cars Using Vegetable Oil as a Diesel Fuel Additive

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***Abstract* — The article is devoted to the method for calculating carbon dioxide emissions of cars using vegetable oil as a diesel fuel additive. The method based on the fundamental principles of the theory of automobiles and supplemented by revealed patterns allows for analytical calculation of carbon dioxide emissions when using mixed fuels. The method used for calculating carbon dioxide emissions involves using dependencies between specific effective consumption, effective power and the share of rapeseed oil in fuel mixture.**

***Keywords* — carbon dioxide emissions, specific effective consumption, rapeseed oil in fuel mixture, biofuel, fuel consumption**

I. INTRODUCTION

Currently, petroleum products are the most important component of everyday life. Industries and individuals use hydrocarbons as a form of energy. There is a problem of limited reserves of petroleum products, since their recovery period is 50–350 million years. Taking into account the degree of consumption of resources as of 2017–2018, it has been established that oil reserves (about 3,000 billion barrels) will be exhausted in 93 years. Due to limited reserves, prices for gasoline and diesel fuel are rising which affects prices of other products. Therefore, it is necessary to search for alternative energy sources [1, 2]. Along with the growing consumption of petroleum fuel, the amount of greenhouse gases, in particular carbon dioxide, emitted into the atmosphere also increases.

A promising source is energy of renewable natural resources (hydrogen fuel, electrical energy, biofuel). The use of plant components as an independent source of fuel and a fuel additive is one of the development areas for the fuel power engineering [3–6].

Biofuel as an energy source is used in injection oil (diesel) engines. As a rule, sunflower, rapeseed, corn, soybean, peanut and palm oils are used as fuel additives [7–10]. The engine operating on biofuel with a small share of plant components does not require changes in the design of fuel supply devices and engine design features. However, the use of biodiesel increases fuel consumption due to the increased oxygen content in the fuel mixture. One of the positive aspects of biotopes is reduced smokiness and the lower amount of harmful substances emitted into the environment [4, 5, 11, 12]. Thus, diesel engines are more environmentally friendly [9, 13].

It is necessary to develop a method that takes into account changes in carbon dioxide emissions when using biofuel.

II. THEORETICAL BACKGROUND

Let us calculate the consumption of fuel by a car, g/km [14]:

$$Q_S = \frac{g_e}{V_a \cdot \eta_{tr}} \left(N_\psi + N_w + N_j \right) \tag{1}$$

where g_e – specific effective fuel consumption, g/kW·h;

V_a – speed, *km/h*;

η_{tr} – transmission efficiency;

N_ψ – total power of road resistance losses, *kW*;

N_w – power of aerodynamic losses, *kW*:

N_j – power of inertia resistance, *kW*.

The transmission efficiency is calculated by formula:

$$\eta_{tr} = 0{,}99^K \cdot 0{,}97^L \cdot 0{,}98^M \tag{2}$$

where *K*, *L*, *M* – the number of pairs of cylindrical, bevel or hypoid gears, cardan joints involved in the torque transmission of torque for a certain gear.

The power of road resistance losses, kW is calculated by formula:

$$N_\psi = \frac{F_\psi V_a}{3{,}6} \tag{3}$$

where F_ψ – total power of road resistance losses, *H*.

The total power of road resistance losses taking into account the rode slope, *kW* is calculated by formula:

$$F_\psi = m_\text{п} \cdot g \cdot (f \cdot \cos\alpha + \sin\alpha) \tag{4}$$

where f – rolling resistance coefficient;

$m_\text{п}$ – gross vehicle weight, kg;

g – acceleration of gravity, *m/s²*.

α – road angle, *degrees*

The rolling resistance coefficient depends on the speed:

$$f = f_0 \cdot (1 + \frac{V_a^2}{20000}) \tag{5}$$

where f_0 – rolling resistance coefficient (for the asphalt road $f_0 = 0{,}018$; for the earth road $f_0 = 0{,}03$).

The aerodynamic loss power *kW* is calculated by formula:

$$N_w = \frac{F_w \cdot V_a}{3{,}6}, [kWt] \tag{6}$$

where F_w – aerodynamic loss power, *H*.

The aerodynamic loss power is calculated by formula:

$$F_w = K_w \cdot S_x \cdot \left(\frac{V_a}{3{,}6}\right)^2 \tag{7}$$

where К_w – streamlined shape coefficient, *kg/m³*;

S_x – the area of automobile projection on a plane perpendicular to the longitudinal axis, *m²*.

$$K_\text{в} = 0{,}5 \cdot c_w \cdot \rho_w \tag{8}$$

where c_w – drag coefficient;

ρ_w – air density, *kg/m³*.

The vehicle speed in each gear, *km/h* is calculated by formula:

$$V_a = 0{,}377 \frac{r_k \cdot n_e}{i_{tr}}, [km/h] \tag{9}$$

where r_k – kinematic wheel rolling radius, *m*

i_{tr} – transmission ratio;

n_e – crankshaft rotation frequency, *rpm*.

$$i_{tr} = i_{gb} \cdot i_{mg} \tag{10}$$

where i_{gb} – gear ratio;

i_{mg} – drive gear ratio.

The calculated value of the specific effective fuel consumption for mixtures consisting of vegetable oil and diesel fuel can be described by the following formula:

$$g_e = \frac{3600}{\eta_e \cdot H_u}, [\frac{g}{kWt \cdot h}] \tag{11}$$

where η_e – effective efficiency factor; H_u – lower heat value, MJ/kg.

The effective efficiency factor η_e is calculated by formula:

$$\eta_e = \eta_i \cdot \eta_m \tag{12}$$

where η_i – indicator efficiency factor; η_m – mechanical efficiency factor.

The lower heat value H_u is calculated by formula:

$$H_u = \delta_{do} \cdot H_u^{df} + \delta_{vo} \cdot H_u^{vo} \tag{13}$$

where δ_{do} and δ_{vo} are the shares of diesel fuel and rapeseed oil in fuel mixture, respectively; H_u^{df} and H_u^{vo} is the lower heat value of DF and RO, respectively (42,437 MJ/kg and 36,992 MJ/kg [15, 16]).

It is known that for complete combustion of one kg of carbon, $\frac{8}{3} g_c$ of oxygen is required. Assuming the complete reaction, the total mass of carbon is calculated by formula:

$$m_{CO_2}^{sum} = Q_S\left(\frac{8}{3} g_c + g_c\right) = Q_S \frac{11}{3} g_c, [g/km] \tag{14}$$

where Q_S is the travel fuel consumption, *g/km*; g_c is the mass fraction of carbon in fuel, *kg.*

The total mass fraction of carbon depending on the mass fraction of vegetable oil in fuel mixture is:

$$g_c^{sum} = \delta_{vo} \cdot g_c^{vo} + (1 - \delta_{vo}) g_c^{df} \tag{15}$$

where δ_{vo} is the mass fraction of rapeseed oil in fuel mixture; g_c^{vo} is the mass fraction of carbon in the diesel fuel (0,864 [15,16]); g_c^{df} is the mass fraction of carbon in rapeseed oil, respectively (0,776 [15,16]);

The mass of carbon dioxide is calculated by formula:

$$m_{CO_2}^{df} = Q_S \frac{11}{3} (g_c^{sum} - g_c^{vo} \cdot \delta_{vo}), [g/km] \tag{16}$$

In (1, 11, 12), unknown values are the values of the effective efficiency, or the specific effective fuel consumption. To find the latter, empirical dependence $g_e = f(N_e, \delta_{vo})$ can be used.

III. MATERIALS AND METHODS

An engine TD-27 engine with a mileage of more than 200 thousand km installed on a test bench was studied. The studies were carried out in accordance with the modes of external speed characteristics (ESC) and load characteristics (LC). The engine torque and crankshaft rotation frequency were measured using test bench data. Fuel consumption was measured using electronic scales. The experiment was carried out sequentially: pure DF – 40 % RO mixture (at a pitch of 10 %). The maximum value of the share of vegetable (rapeseed) oil depended on mixture pumpability and low-temperature properties.

Calculation of carbon dioxide emissions for mixed fuels (rapeseed oil + diesel) uses formulas 1–16.

Calculation of CO_2 emissions was carried out for a real car moving without acceleration on asphalt and earth roads at a constant crankshaft rotation frequency of 2200 rpm and in various gears (based on calculated load characteristic and driving modes). When the vehicle is moving with acceleration and the pedal is fully depressed, it is advisable to use dependence $g_e = f(n_e, \delta_{vo})$.

Initial characteristics of the car are presented in Table 1

TABLE I. INITIAL CHARACTERISTICS OF THE CAR

Characteristics	**Value**
Gearbox ratios	$i_{gb1} = 3{,}786$ $i_{gb2} = 2{,}188$ $i_{gb3} = 1{,}304$ $i_{gb4} = 1{,}0$ $i_{gb5} = 0{,}794$
Number of pairs of cylindrical gears	*K=2*
Number of pairs of conical or hypoid gears	*L=1*
Number of cardan joints	*M=2*
Number of wheels	4
Gross vehicle weight, kg	$m_a = 2785\ kg$
Kinematic wheel radius, m	$r_k = 0{,}33\ m$
Midship area, *m*^{2}	$S_x = 3{,}774\ m^2$
Drag coefficient	$c_w = 0{,}4$

IV. RESULTS AND DISCUSSION

As a result of the experimental studies, the target dependences were determined: $g_e = f(N_e, \delta_{vo})$ at n_e = const = 2200 rpm), $g_e = f(n_e, \delta_{vo})$ (full loading). They were built in the form of response surfaces and approximated in MatLab (Fig 1 and 2).

1) The equation of specific effective fuel consumption and load changes at constant engine crankshaft rotation frequency and vegetable oil share in fuel mixture:

$$g_e = 611.7 - 30.93 \cdot Ne + 370.3 \cdot \delta_{vo} + \\ +0.711\, N_e^2 - 7.804\, Ne \cdot \delta_{vo}\,. \qquad (17)$$

2) The equation of specific effective fuel consumption and changes in the crankshaft rotation frequency and PM share at full loading:

$$g_e = 506.9 - 81.96\delta_{vo} - 0.2816n_e + 459.9 \cdot \delta_{vo}^2 - \\ -0.031n_e \cdot \delta_{vo} + 0.0001n_e^2. \qquad (18)$$

Selection of dependences and coefficients of coupling equations allowed for the conclusion that the method can be used for alternative types of fuel, including a mixture of diesel fuel and vegetable oil. The coupling equations and their parameters are presented in Table 2.

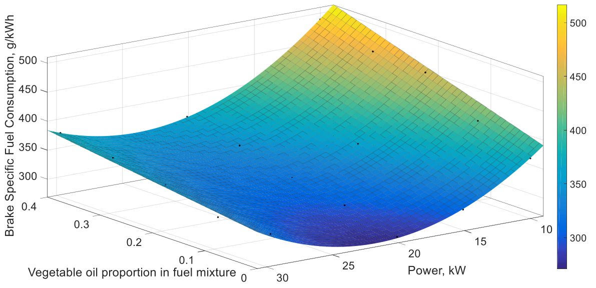

Fig. 1. Dependence of the specific effective consumption on the effective power and the share of rapeseed oil in fuel mixture (according to the load)

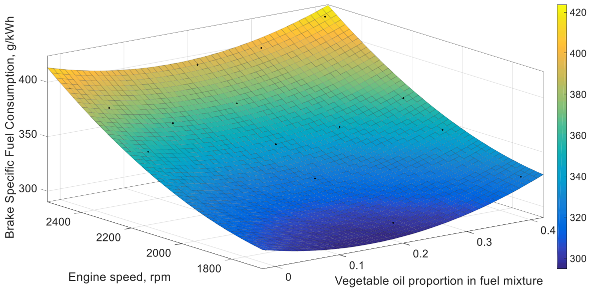

Fig. 2. Dependence of the specific effective fuel consumption on the crankshaft rotation frequency and the share of rapeseed oil in fuel mixture (according to the external speed)

The processing of indicator diagrams made it possible to determine the dependence of the ignition delay period on the crankshaft rotation frequency and the share of oil in fuel mixture. The results are presented in Figure 3.

Figure 3 can be used to estimate rigidity of the working process when physical and mechanical properties of the fuel change. Due to the lower cetane number, rigidity of the working process increases if the oil share is 40 % and more. When using fuels with an oil share of more than 30 %, additional measures are required (additives increasing the cetane index [17]). The ignition delay period may increase twice as compared with that when using pure diesel fuel (Fig. 3).

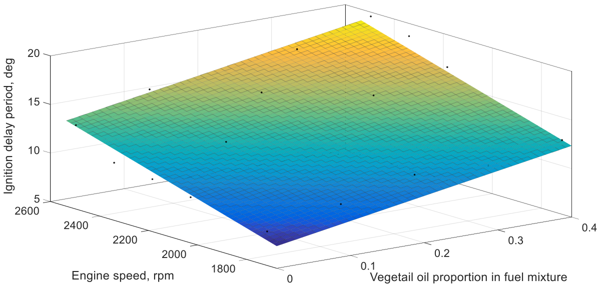

Fig. 3. Dependence of the ignition delay period on the crankshaft rotation frequency and the share of vegetable oil in fuel mixture

TABLE II. FUNCTIONAL DEPENDENCIES AND THEIR STATISTICAL PARAMETERS

Function	Coupling Equation	Statistical parameters		
		SSE	***Adj R²***	***RMSE***
$g_e=f(N_e,\delta vo)$ $(n_e=const)$	$g_e=611.7-30.93N_e+$ $+370.3\cdot\delta_{vo}+0.711N_e^2-$ $-7.804N_e\delta_{vo}$	1114	0.98	8.62
$g_e=f(n_e,\delta vo)^2$	$g_e=506.9-81.96\ \delta_{vo}$ – $-0.2816\ n_e + +459.9\cdot\delta_{vo}^2-$ $-0.031\ n_e\cdot\ \cdot\delta_{vo}+0.0001n_e^2$	1448	0.936	8.73
$\phi_{id} = f(n_e,\delta vo)$	$\varphi_{id} = -5.296\ +13.38\cdot\delta_{vo}+$ $+0.0075\cdot n_e$	25.03	0.87	1.067

Fuel efficiency of the car moving on horizontal asphalt and earth surfaces was calculated using equation (17).

The results are presented in Figures 4 and 5.

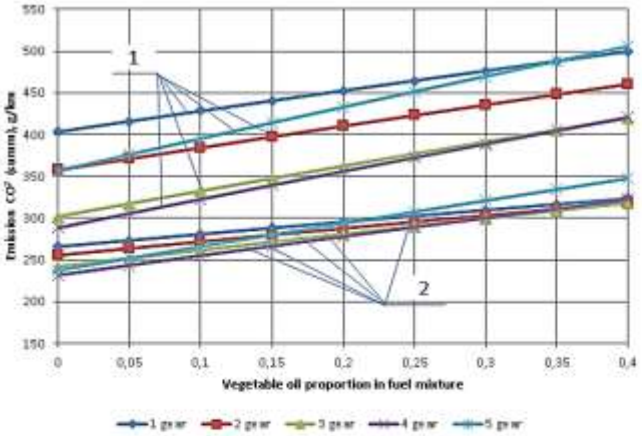

Fig. 4. Dependence of total emissions of carbon dioxide on the mass content of vegetable oil in fuel mixture during car movement at a constant crankshaft rotation frequency in different gears. *(1 – Earth road (f_0=0.03); 2 – Asphalt road (f_0=0.018))*

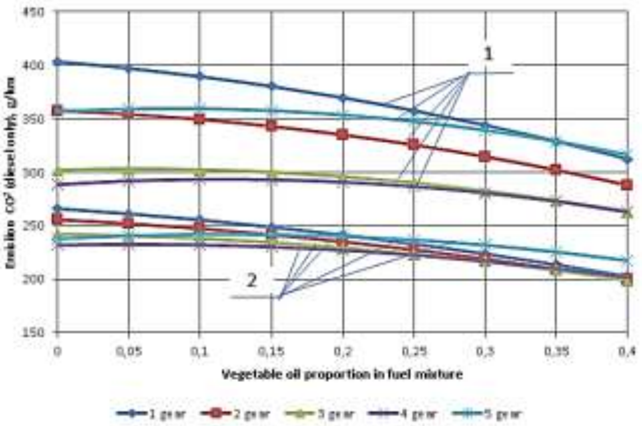

Fig. 5. Dependence of non-renewable emissions of carbon dioxide on the share of vegetable oil in fuel mixture during car movement at a constant crankshaft rotation frequency in different gears *(1 – Earth road (f_0=0.03); 2 – Asphalt road (f_0=0.018))*

The analytical calculation showed that at a constant crankshaft rotation frequency in each gear, with an increase in the share of oil in fuel mixture, the total mass of CO_2 emissions increases, and the fuel economy deteriorates. This effect is due to a decrease in the lower heat of fuel combustion with an increase in the share of vegetable oil (equation (13)). At the same time, the use of rapeseed oil as a fuel additive makes it possible to use carbon participating in the natural cycle and return it to the same circulation medium. Therefore, a graph taking into account mass emissions and ignoring carbon dioxide emissions caused by rapeseed oil combustion was built (Fig. 5). The analysis of data presented in Figure 5 shows that mass emissions of carbon dioxide decrease in all gears with an increase in the share of rapeseed oil in fuel mixture.

Thus, despite the increased fuel consumption, addition of vegetable oil reduces non-renewable emissions of carbon dioxide into the atmosphere. Further studies will help calculate CO_2 emissions in a wider range of vehicle operation modes, including driving cycles.

V. CONCLUSION

1. The method based on the fundamental principles of the theory of automobiles and supplemented by revealed patterns allows for analytical calculation of CO_2 emissions when using mixed fuels.

2. The method used for calculating CO_2 emissions involves using dependencies $g_e = f(N_e, \delta_{vo})$ (at ne = const), $g_e = f(n_e, \delta_{vo})$ (full loading). It can be used for determining automobile operation modes, including driving cycles.

3. Despite the increased fuel consumption, the addition of vegetable oil reduces non-renewable CO_2 emissions of into the atmosphere.

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