Calculation methods for determining of fuel consumption per hour by transport vehicles

S I Krivoshapov, A I Nazarov, M I Mysiura, I A Marmut, V A Zuyev, V V Bezridnyi, V N Pavlenko

1Department of Technical operation and service of cars, Kharkov National Automobile and Highway University, 25 Yroslava Mudrogo Street, Kharkov, Ukraine

tesa@khadi.kharkov.ua

Abstract. The paper proposes a mathematical model by which it is possible to calculate the hourly fuel consumption for an internal combustion engine operating at idle mode or with a constant load. Simplification of the technique consisted in the calculation of the coefficients of filling the engine cylinders and the excess air through the approximation by polynomials of the first and second degree. It is established that when the engine is running without load, the hourly fuel consumption increases in proportion to the rotational speed of the crankshaft and the engine displacement. Examples of calculating the standard fuel consumption at idle mode with the engine off without a load are given for a Skoda Octavia 1.6 MPI with a gasoline engine and a Skoda Octavia 2.0 TDI with a diesel engine. Graphic dependencies of the hourly fuel consumption change on the crankshaft rotation speed for the petrol and diesel Skoda Octavia were obtained. The calculation was carried out and graphical dependencies of fuel consumption were obtained when special equipment was operated using the example of the KrAZ-6322 car. It is proposed to use deterministic methods for determining fuel consumption in road transport.

1. Introduction

Fuel efficiency is one of the quality indicators of transport vehicles. Fuel consumption is a significant part of the operating costs of a car. In the structure of the cost of transport operations, the consumption of fuels and lubricants accounts for 40-50% of all costs [1].

In all countries coming from the Soviet Union, fuel consumption in road transport is controlled at the legislative level. In Ukraine, this is an order of the Ministry of Transport No. 43 of 1998 [2], which fixes the normative value of the basic consumption rate for each car, stipulates the conditions for additional fuel consumption and introduces corrective factors for changing the flow rate depending on operating conditions. Similar principles are laid down in the standards: Russia [3], Belarus [4], Moldova [5], Kazakhstan [6], etc.

The disadvantage of the existing methodology is the limited number of car brands for which a basic fuel consumption rate has been established, and the lack of a mechanism for independently expanding the range of standards for new rolling stock.

This problem can be solved by creating a mathematical model that relates fuel consumption to the technical data of the car, taking into account the conditions of its operation.

The aim of this work is to develop a mathematical model for calculating the hourly fuel consumption during engine operation without load and with a fixed constant load on the internal combustion engine.
2. Exposition

Rationing of fuel consumption according to the method [2] is determined through the flow rate in l/100 km.

Hourly consumption is used when the car engine is running without movement in the following cases:

- in case of forced downtime of the car during loading and unloading of goods or passengers, production necessity and downtime in traffic jams during rush hour;
- when starting and warming up gas-filled cars;
- during the operation of specialized equipment with a stationary vehicle;
- the operation of autonomous engines used to drive specialized equipment while driving and stopping the vehicle.

For transport vehicles, hourly consumption is determined through the basic rate of fuel consumption [2]. So the hour of forced downtime is equivalent to 5 km of the car. The start-up norm for a gas-balloon vehicle is (0.5 ... 5.0) % of the base vehicle’s liquid fuel consumption per day of operation, depending on the air temperature.

For specialized mobile and autonomous engines, the hourly norm should be numerically presented in the normative [2] for a specific vehicle and equipment.

On the other hand, the hourly fuel consumption can be determined analytically through the speed and load characteristics of the engine, using the dependences from the theory of engines [7].

Hourly consumption determines fuel consumption in kilograms or liters per hour of operation of a power plant. For transport vehicles, it is more common to record fuels and lubricants in liters, and for autonomous engines and construction vehicles in kg / h.

Hourly fuel consumption in l / h:

\[
G_t = \frac{q_e \cdot N_e}{1000 \cdot \rho_t},
\]  

(1)

where:
- \( q_e \) - specific effective fuel consumption, g / (kW ∙ h);
- \( N_e \) - effective power, kW;
- \( \rho_t \) - fuel density, g / cm³ (kg / l).

Effective specific fuel consumption:

\[
q_e = \frac{3600 \cdot 10^3}{\eta_e \cdot H_n},
\]  

(2)

where:
- \( \eta_e \) - effective engine efficiency;
- \( H_n \) - fuel calorific value, kJ / kg.

Effective engine efficiency:

\[
\eta_e = \eta_i \cdot \eta_m,
\]  

(3)

where:
- \( \eta_i \) - engine efficiency indicator;
- \( \eta_m \) - mechanical engine efficiency.

Indicator engine efficiency:

\[
\eta_i = \frac{P_i \cdot L_0 \cdot R \cdot T}{H_n \cdot \eta_e \cdot P} \cdot \alpha,
\]  

(4)

where:
- \( P_i \) - average indicator pressure, kPa;
- \( L_0 \) - stoichiometric amount of fuel-air mixture, kmol / kg;
- \( R \) - universal gas constant, J / (mol ∙ K);
- \( T \) - air temperature, K.
\( \eta_v \) - engine cylinder fill ratio;  
\( P \) - air pressure, kPa;  
\( \alpha \) - excess air ratio.

The coefficient of excess air depends on the load on the engine. In figure 1 shows a graphical dependence of the coefficient of excess fuel on the percentage of used power [8].

![Graph showing the relationship between excess air ratio and percentage of power used for diesel (a) and gasoline (b) ICEs.](image)

The percentage of power used, %  
Excess air ratio  

**Figure 1.** Change in the coefficient of excess air from the percentage of power use: (a) - diesel ICE, (b) - gasoline ICE

This relationship can be approximated by a polynomial of the second degree of the form:

\[
\alpha = A_{\alpha} \cdot N_1^2 + B_{\alpha} \cdot N_1 + C_{\alpha},
\]

where:  
\( N_1 \) - power utilization percentage, %;  
\( A_{\alpha}, B_{\alpha}, C_{\alpha} \) - empirical coefficients depending on engine type.

The values of these coefficients can be taken:

- for diesel:  
  \[ A_{\alpha} = 3 \cdot 10^{-4}, \quad B_{\alpha} = -0.06, \quad C_{\alpha} = 5.0; \]

- for gasoline:  
  \[ A_{\alpha} = -1 \cdot 10^{-4}, \quad B_{\alpha} = 0.012, \quad C_{\alpha} = 0.85. \]

The engine fill factor also depends on the load. In figure 2 shows this dependence [8].

The result of approximating a linear function of the form:

\[
\eta_v = A_\eta \cdot N_1 + C_\eta,
\]

where:  
\( A_\eta, B_\eta \) - empirical coefficients depending on engine type.

The values of these coefficients can be taken:

- for diesel:  
  \[ A_\eta = 9 \cdot 10^{-4}, \quad B_\eta = 1.0; \]

- for gasoline:  
  \[ A_\eta = 7 \cdot 10^{-3}, \quad B_\eta = 0.17. \]
Figure 2. The change in the filling ratio of the percentage of power use: (a) - diesel ICE, (b) - gasoline ICE

Power utilization percentage:

\[ N_1 = \frac{N_e}{N_{e_{\text{max}}}} \times 100 \]  

(7)

where: \( N_{e_{\text{max}}} \) - maximum effective engine power, kW;

Average indicator pressure:

\[ P_i = \frac{P_e}{\eta_m} \]  

(8)

where: \( P_e \) - average effective pressure, kPa;

Mechanical efficiency:

\[ \eta_m = \frac{P_e}{P_e + P_m} \]  

(9)

where: \( P_m \) - pressure of mechanical losses, kPa;

Average effective pressure:

\[ P_e = \frac{N_e \cdot 30 \cdot \tau \cdot 10^3}{V_h \cdot n} \]  

(10)

where: \( \tau \) - engine cycle; 
\( V_h \) - engine displacement (all cylinders), l; 
\( n \) - engine rotation speed, rpm. 

The average pressure of mechanical losses:

\[ P_m = a_m + b_m \cdot W_n \]  

where: \( W_n \) - average piston speed, m / s;
\( a_m, b_m \) - mechanical loss factors in the engine.

\[
W_n = \frac{30 \cdot S_n}{n},
\]

where: \( S_n \) - cylinder height (distance from TDC to BDC), m.

After substitution, we obtain the expression for determining the hourly fuel consumption in l / h:

\[
G_i = \frac{0.12 \cdot P \cdot V_h \cdot n}{L_0 \cdot R \cdot T \cdot \tau \cdot \rho_t} \cdot \frac{B_\eta + \frac{10^2 \cdot A_n \cdot N_{e}}{N_{e_{max}}} + \frac{10^4 \cdot A_n \cdot N_{e}^2}{N_{e_{max}}}}{C_a + \frac{10^2 \cdot B_\alpha \cdot N_{e}}{N_{e_{max}}} + \frac{10^4 \cdot A_\alpha \cdot N_{e}^2}{N_{e_{max}}}}.
\]

If the effective power is excluded from the equation, i.e. \( N_e = 0 \), then equations (12) will be:

\[
G_i = \frac{0.12 \cdot P \cdot V_h \cdot n \cdot B_\eta}{L_0 \cdot R \cdot T \cdot \tau \cdot C_a \cdot \rho_t}.
\]

Equation (13) can be used to calculate fuel consumption when the engine is running without load, and equation (12) to determine the additional flow to the auxiliary equipment drive.

In the formula (13) as constant values are used: \( R = 8.31 \) J / (mol * K) and \( \tau = 4 \).

For vehicles with gasoline engine: \( \rho_t = 0.76 \) g / cm\(^3\), \( L_0 = 0.5119 \) kmol / kg, \( B_\eta = 0.17 \), \( C_a = 0.85 \). Then the formula (13) will be simplified:

\[
G_i = 0.00185 \cdot V_h \cdot P / T \cdot n.
\]

For diesel cars, the following indicator values can be accepted: \( \rho_t = 0.84 \) g / cm\(^3\), \( L_0 = 0.495 \) kmol / kg, \( B_\eta = 1.0 \), \( C_a = 5.0 \). Then formula (13) takes the form:

\[
G_i = 0.00174 \cdot V_h \cdot P / T \cdot n.
\]

The temperature and air pressure during the intake \( P \) and \( T \) compression process in the engine cylinders rises. We assume that their change is proportional. Then under and accept the parameters of the atmospheric air. Under normal conditions: \( P = 101.325 \) kPa and \( T = 293 \) K. Then: \( P / T = 0.346 \).

Let's calculate the hourly fuel consumption using the example of a Skoda Octavia 1.6 MPI car with a gasoline engine. For this car we will accept the following initial data: \( n_{min} = 800 \) rpm. and \( V_h = 1.6 \) l. Then the hourly fuel consumption at idle will be:

\[
G_i = 0.00185 \cdot 1.6 \cdot 0.346 \cdot 800 = 0.808 \text{ l/h}.
\]

Let's calculate the hourly fuel consumption of a Skoda Octavia 1.9 TDI diesel car with the following initial data: \( V_h = 1.9 \) l and \( n_{min} = 600 \) rpm. Then the hourly fuel consumption at idle will be:

\[
G_i = 0.00175 \cdot 2.0 \cdot 0.346 \cdot 600 = 0.673 \text{ l/h}.
\]

The consumption of a diesel car at idle is less than gasoline due to lower crankshaft revolutions and a more economical engine.

In figure 3 shows a graph of changes in hourly fuel consumption for Skoda Octavia 1.6 MPI and 1.9 TDI vehicles. With an increase in engine speed, fuel consumption increases proportionally.
We calculate the standard fuel consumption for Skoda Octavia cars according to the method of rationing fuel consumption [2]. For a Skoda Octavia car with an AVU engine with a displacement of 1.6 l and a power of 75 kW, the basic rate of gasoline consumption is set at 7.5 l / 100 km. Then at 5 km the car will spend: 375.0100/55.7 = l. Therefore, according to the method [2], the fuel consumption of a Skoda Octavia will be 0.375 l / h. A Skoda Octavia car with an AGR diesel engine with a working volume of 1.9 l and a power of 66 kW, for which the basic rate of gasoline consumption is set at 5.2 l / 100 km, according to the method [2], the hourly fuel consumption will be 26.0100/52.5 = l / h. The hourly fuel consumption obtained by the method [2] is significantly lower than the calculated values obtained by the formula (13). Experimental studies have shown idle fuel consumption for Skoda Octavia 1.6 MPI – 0.7 ... 0.8 l / h, and for Skoda Octavia 1.9 TDI – 0.6 ... 0.7 l / h. These data are consistent with our calculations.

We will calculate the fuel consumption for specialized equipment installed on the chassis of the KrAZ-6322 car. The following indicators are accepted for this car: $V_\text{h} = 14.86$ 1, $N_{\text{e max}} = 243$ kW, $\rho = 0.84$ g / cm³, $A_\eta = 9 \cdot 10^{-4}$, $B_\eta = 1.0$, $A_\alpha = 3 \cdot 10^{-4}$, $B_\alpha = -0.06$, $L_\eta = 0.495$ kmol / kg, $C_\alpha = 5.0$. After substituting in the formula (12) the hourly fuel consumption for this car can be calculated as follows:

$$G_t = \frac{864 \cdot n \cdot (N_\text{e} / 2700 + 1)}{N_\text{e}^2 - 486 \cdot N_\text{e} + 9.8 \cdot 10^4}$$

In figure 4 shows a graph of the change in hourly fuel consumption for the KrAZ-6322 car at different engine speeds of the YaMZ-238 diesel engine.

If specialized equipment that works at a frequency of 1,500 rpm and consumes 25 kW of power is connected to the car, the hourly consumption of the KrAZ-6322 will be:

$$G_t = \frac{864 \cdot 1500 \cdot (25 / 2700 + 1)}{25^2 - 486 \cdot 25 + 9.8 \cdot 10^4} = 15.05 \text{ l / h}.$$
3. Conclusion
The current fuel consumption rating system in Ukraine is not perfect. By modeling the processes of the functioning of the system, taking into account the design features and operating conditions, it is possible to get by calculation the standard values of the fuel consumption of a particular car according to its technical and operational characteristics.

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