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RESEARCH ARTICLE

The Calculation of the Fuel Cost for a Car

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Abstract

The proposed formula derived considering the physical phenomena which occur during truck operation makes it possible to calculate fuel cost during the operation more accurately. The results of comparison of calculations by the proposed formula with test results tractors parties "TransEuroTest" are presented. The results of the calculation with the help of new formula differ from the experimentally obtained values of the fuel consumption of vehicles for not more than 1%. The average fuel consumption of tractors at an average speed is shown. The proposed formula for calculating the cost makes it easy to compare the fuel consumption of different vehicle options. The formula can also be used when evaluating the effect of vehicle weight on fuel consumption, which is impossible according to the well-known formulas.

Keywords

car, fuel consumption, operating conditions, road resistance, speed

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1 Introduction

Fuel costs in the cost structure of freight road transport reach up to 30-35 %. In connection with the increase in prices for energy resources, tightening of requirements for environmental performance of vehicles, the relevance of reducing the fuel consumption of vehicles increases (Bokor, 2012; Borkowski et al., 2013). The vast majority of vehicles buyers in assessing the feasibility of indicators put the fuel consumption in the first place, therefore there is a need of evaluation of fuel consumption of the vehicle and the search of ways of its reduction (Ildarkhanov, 2015; 2018; Ildarkhanov et al., 2015). Well-known formulas of calculation of the fuel consumption of the truck do not objectively take into account both technical parameters and conditions (Török et al., 2014; Vass et al., 2013; Zöldy et al., 2015).

2 Materials and methods

Currently, the consumption rate of fuel is calculated by the well-known formula (Ipatov, 1982)

$$S_t = \left(Q_{f1} + Q_{f2} q\gamma\beta\right) K_{year} K_{\text{wint}} C_f \,/\, 100, \qquad (1)$$

where

Q_{f1} − is a linear rate of fuel consumption, l/100 km;

Q_{f2} − is the rate of fuel consumption per transport work: for vehicles with carburetor Q_{f2} = 1.9 l/100 t · km; with the diesel engine Q_{f2} = 1.3 l/100 t · km;

q − capacity, t;

γ − is the coefficient of the cargo class;

β − is the coefficient of using mileage;

K_{year} − is the annual mileage, km;

K_{wint} − is a coefficient which takes into account increased fuel consumption in winter conditions, K_{wint} = 1.04 ... 1.08;

C_f − is the price of 1 liter of fuel.

The formula (1) in the early stages of the vehicle design cannot be applied, because linear flow rate of the new model is still unknown and the rate of fuel consumption per transport work in different cars may vary significantly. In addition, the formula does not take into account operating conditions such as speed, road resistance, the presence of devices aimed at reducing fuel consumption, which determine ultimately the cost of fuel.

In this formula, the rate of consumption per transport work – Q_{f2} for all cars with a single type of engine is adopted the same, that is not true as the specific capacity of vehicles is different.

The fuel consumption of a vehicle shall be calculated taking into account the physical phenomena occurring during transportation of cargo, which is the destination of a truck (Andrejszki et al., 2014; Salling et al., 2017). Physical work during the freight of cargo, made by the vehicle during the year, is defined as the product of the efforts, developed by the car, and the mileage. Considering the mileage of the car with and without load, operation of cargo transportation can be calculated by the formula

$$A_a = f\left(\beta\left[\left(G_{mv}+G_{mtr}\right)+\gamma\left(q_v+q_{tr}\right)\right]+\left(1-\beta\right)\left(G_{mv}+G_{mtr}\right)\right)K_{year}, \tag{2}$$

where

G_{mv}, G_{mtr} – are the laden mass of the vehicle and trailer respectively, kg;

q_v – is the capacity of the vehicle, kg;

q_{tr} – is the capacity of the trailer, kg;

f – is the coefficient of road resistance which is determined by the following formula according to driving on different types of the roads

$$f = \sum_{i=1}^{r} \alpha_i f_i, \tag{3}$$

where

f_i – is the coefficient of road resistance on the road of i type;

α_i – is the percentage of vehicle mileage on the road of i type;

r – is the number of types of roads on which the vehicle is operated.

Under the law of conservation of energy, the work done during transportation of cargo shall be equal to the work obtained from the combustion of fuel in the engine, and the part that is to perform mechanical work (Zaabar et al., 2010). This work can be defined by the formula

$$A_t = \rho H V \mu_{eng}\mu_p\mu_v, \tag{4}$$

where

ρ – is the density of the fuel to be used on this vehicle, kg/l, for example, for gasoline it is 0.78 kg/l, for diesel fuel – 0.98 kg/l, for kerosene – 0.8 kg/l;

H – is the heat of combustion, J/kg;

V – the volume of fuel required to perform this work, l;

μ_v – is the coefficient which takes into account the presence of special equipment for reducing fuel consumption;

μ_{eng} – is the total efficiency of the internal combustion engine, for a carburetor engine it equals to $\mu_{eng} = 0.20 \div 0.30$, for diesel $0.30 \div 0.35$, for gas $0.22 \div 0.28$;

μ_p – is the powertrain efficiency, which is in the range of $0.80 \div 0.95$.

From the condition of equality of transport work and mechanical work of the engine according to the Eq. (2) and (4) we find the annual consumption of fuel (l) for a truck

$$\begin{aligned} V &= 1.01K_{wint}K_{year}f\left[\beta\left(G_m+\gamma q\right)+\left(1-\beta\right)G_m\right] \\ &\left(1.05\vartheta_f/\vartheta_n-0.05\right)10^4\left(1+g_f/100\right)^t \\ &/\left(\rho H\mu_{eng}\mu_p\mu_v\right), \end{aligned} \tag{5}$$

where

g_f – is the annual growth rate of fuel consumption due to the vehicle aging, %;

t – is the ordinal number of the year.

The ratio of 1.01 in the formula takes into account the consumption of fuel on the rise over the savings when rolling downhill, because the engine does not turn off completely on the downhills, so fuel saving on downhills is less than the overspending on the rise. To calculate the fuel consumption of the articulated truck the following notation is introduced in Eq. (5)

$$G_m = G_{mv} + G_{mtr}; \tag{6}$$

$$q = q_v + q_{tr}; \tag{7}$$

The formula takes into account the effect of wind load on fuel consumption with the help of empirical coefficient, which is defined by the formula

$$K_\vartheta = 1.05\vartheta_f/\vartheta_n - 0.05, \tag{8}$$

where

ϑ_f – is the vehicle speed, km/h;

ϑ_n – is the basic speed equals to $\vartheta_n = 60$ km/h; when speed $\vartheta_n \leq$ 60 km/h; it is recommended to take $K_v = 1$, since at low speeds the effect of wind load on fuel consumption is insignificant.

At high speeds the fuel consumption of the car is recommended to calculate according to the following formula, which takes into account wind load:

$$\begin{aligned} V &= 1.01K_{wint}K_{year}f\left[\beta\left(G_m+\gamma q\right)+\left(1-\beta\right)G_m+W_w\vartheta_f^2/1.3\right] \\ &10^4\left(1+g_f/100\right)^t/\left(\rho H\mu_{eng}\mu_p\mu_v\right). \end{aligned} \tag{9}$$

Here, the expression $W_w\vartheta_f^2/1.3$ takes into account the wind force. The wind force depends essentially on the W_w – factor of fairness daN · s^2/m^2, which is determined by the design of the car. The values of W_w for trucks are in the range from 0.18 to 0.35 daN · s^2/m^2. In the formula (9) the vehicle speed ϑ_f is in m/s.

Formulas (5) and (9) consider the excellence of the engine, powertrain, road conditions, load capacity and laden mass of the vehicle and trailer, the speed of movement, load of the vehicle, the availability of equipment specifically designed to reduce fuel consumption, the calorific value of used fuel, i.e. all the factors, which take into account the physical nature of the freight by vehicle.

Annual fuel costs in rubles will amount to

$$S_f = VC_f, \quad (10)$$

where

C_f − is the cost of one liter of fuel, rub.

Let's consider the example of a fuel consumption calculation using Eq. (5) for a vehicle KAMAZ-5320 on smooth asphalt (f = 0.018) (Velikanov, 1977) with the following data:

$$G_m = 7080kg;\ q = 8000kg;\ \beta = 1;\ \gamma = 1;\ K_{year} = 100km;$$
$$\mu_{eng} = 0.30;\ \mu_p = 0.89;\ \mu_v = 1;\ H = 42.7 \cdot 10^6 J/kg;$$
$$\rho = 0.98kg/l;\ \vartheta_f = 60km/h.$$

Substituting this data in Eq. (5) when g_f = 0, we find (l)

$$V = 1.01 \cdot 1.04 \cdot 100 \cdot 0.018 \cdot [7080 + 8000] \cdot (1.05 \cdot 60/60 - 0.05)10^4 / (0.98 \cdot 42.7 \cdot 10^6 \cdot 0.30 \cdot 0.89 \cdot 1) = 25.5.$$

Reference fuel consumption of a loaded truck KAMAZ-5320 with the full weight of 15080 kg at a speed of 60 km/h on asphalt is V_r = 26.0 l/100 km (Ildarkhanov, 2014). The difference between the experimental refrence value of fuel consumption and the calculated value is the following

$$\Delta = (V_r - V)/V_r \cdot 100 = (26 - 25.5)/26 \cdot 100 = 1.9\%, \quad (11)$$

i.e. less than 2 %.

Let's determine the fuel consumption of this car in the articulated truck for the above conditions, if the total weight of the articulated truck is equal to $G = G_m + q$ = 26805 kg. Condition: asphalt road of improved quality Dmitrov autorange, for which f = 0.014 (Velikanov, 1977).

The estimated fuel consumption per 100 km at g_f = 0

$$V = 1.01 \cdot 1 \cdot 100 \cdot 0.014 \cdot 26805 \cdot (1.05 \cdot 60/60 - 0.05)10^4 / (0.98 \cdot 42.7 \cdot 10^6 \cdot 0.30 \cdot 0.88 \cdot 1) = 34.3l.$$

The experimental value of the reference fuel consumption of the articulated truck is V_r = 35.0 l/100 km (Ildarkhanov, 2014). The difference between experimental value and the calculated one equals to $\Delta = (35.0 - 34.3)/35.0 \cdot 100 = 2$ %.

The accuracy of the proposed formula for calculating fuel consumption of the truck (5) is confirmed by the results of the experiments conducted in the course of a long-term tests (LTT) for vehicles KAMAZ-5320. In LTT the two vehicles KAMAZ-5320 in the range Federal Central Research Institute of Motor Transport in single mode and within the articulated truck KAMAZ-5320+GKB-8350 with a total weight of 26.8 tons at various speeds fuel consumption was measured. The error of measurement of fuel consumption was ± 1%.

The tests were conducted on asphalt concrete road of satisfactory quality (f = 0.018). Total weight of single vehicle was 15.8 tons. The cars before testing were maintained M-1. The tyres from models IN-142B were used on the cars, the pressure in the front tires was equal to 7.3 kg/cm^2, in the rear ones – 4.5 kg/cm^2. Cars and trailers were fitted with awning.

Table 1 shows the results of experiments and calculation of fuel consumption according to Eq. (5). As it can be seen from the table, the error of calculation varies from −23.3 % to +18.2 %, with an average of - 2.2 %.

For one and the same car the error takes different values and for different cars comparison gives different values of the errors. This shows that the estimated Eq. (5) doesn't give the systematic errors, and the differences of experimental values of fuel consumption are associated with changes in fuel consumption during the experiments due to changes of driving conditions of the vehicle, errors in measurement of consumption in tests.

Table 1 The results of experimental measurements and calculating the fuel consumption of KAMAZ-5320

Traffic condition	Experiment				Evaluation due to (5)		Calculating error, %			
	KAMAZ 5320		KAMAZ 5320 + GKB – 8350		KAMAZ 5320	KAMAZ 5320 + GKB – 8350	Vehicle		Articulated truck	
	No. 89	No. 90	No. 89	No. 90			No. 89	No. 90	No. 89	No. 90
Fuel consumption l/100 km due to speed:										
40 km/h	24.7	20.2	29.2	27.2	20.2	25.4	18.2	0.0	13.0	3.6
50 km/h	26.5	21.8	31.6	29.2	23.2	30.9	12.4	-6.4	2.2	-5.8
60 km/h	29.4	24.5	35.4	32.5	30.2	35.4	-2.7	-23.0	0.0	-8.9
70 km/h	33.7	28.7	41.5	37.7	32.0	45.6	5.0	-11.0	-9.8	-21.0
80 km/h	40.2	35.0	50.2	47.1	38.5	53.8	4.2	-10.0	-7.1	-14.0
Main driving cycle, ϑ_f = 70 km/h	33.0	33.2	46.0	46.6	32.0	45.6	3.0	3.6	0.8	2.1
Average value of calculating error, %							6.6	-6.7	-1.5	-7.3

Using experimental and calculated values of fuel consumption, which are given in Table 1, we can assess the significance of regression Eq. (5). Thereto we will calculate the sum of deviations of experimental fuel consumption from the average consumption and the residual amount characterizing the effects unaccounted in Eq. (5) factors on fuel consumption (Table 2).

Table 2 The calculation of the amount of residual and total variance

V_{ex}	V_{calc}	$(V_{ex} - V_{calc})$	$(V_{ex} - V_{calc})^2$	$(V_{ex} - V^*_{calc})^2$
24.7	20.2	4.5	20.25	78.14
20.2	20.2	0.0	0.00	177.95
29.2	25.4	3.8	14.44	18.83
27.2	25.4	1.8	3.24	40.19
26.5	23.2	3.3	10.89	49.56
21.8	23.2	-1.4	1.96	137.82
31.6	30.9	0.7	0.49	3.76
29.2	30.9	-1.7	2.89	18.83
29.4	30.2	-0.8	0.64	17.13
24.5	30.2	-5.7	32.49	81.72
35.4	35.4	0.0	0.00	3.45
32.5	35.4	-2.9	8.41	1.08
33.7	32.0	1.7	2.89	0.02
28.7	32.0	-3.3	10.89	23.42
41.5	45.6	-4.1	16.81	63.36
37.7	45.6	-7.9	62.41	17.30
40.2	38.5	1.7	2.89	44.35
35.0	38.5	-3.5	12.25	2.13
50.2	53.8	-3.6	12.96	277.55
47.1	53.8	-6.7	44.89	183.87
33.0	32.0	1.0	1.00	0.29
33.2	32.0	1.2	1.44	0.11
46.0	45.6	0.4	0.16	155.25
46.6	45.6	1.0	1.00	170.56
805.1			Q_{res} = 265.29	Q = 1566.67

Let's check the null hypothesis about equality to zero the estimated fuel consumption under the accepted factor features H_0: $V = 0$. The total sum of squares of deviations of the effective feature equals to Q = 1566.67, and the residual sum of squares is equal to Q_{res} = 265.29. The smaller Q_{res}, i.e. the influence of unaccounted factors, the better mathematical model corresponds to experimental data. Let's define statistics (Ildarkhanov, 2014).

$$F = \left[\left(Q - Q_{res}\right) / Q_{res}\right] K_2 / K_1$$
$$= \left[\left(1566.67 - 265.29\right) / 265.29\right] \cdot 14 / 9 = 7.63, \quad (12)$$

which has a Fisher - Snedecor distribution with $K_1 = m$, $K_2 = n - m - 1$ degrees of freedom. Here $K_1 = m = 9$ is the number of degrees of freedom or independent variables included in Eq. (5); $K_2 = n - m - 1 = 24 - 9 - 1 = 14$, where n is the number of experimental values of the fuel consumption, taken into account in the analysis. Taking the significance level of the obtained formula $\alpha = 0.05$, the values of K_1 and K_2 from table of F - distribution (Ildarkhanov, 2014) we find the critical value of F

$$F_{0.05;9;14} = 2.65.$$

$F_{0.05;9;14} < F$, so the null hypothesis is rejected, the resulting equation of fuel consumption (5) is significant and can be applied in practice.

A significant impact on fuel consumption have road conditions that take into account the rolling resistance coefficient f, which varies within wide limits for the same road, for example, for asphalt roads f = 0.014 ... 0.018, i.e. the ratio between extreme values is equal to 1.28. This circumstance reduces the dignity of Eq. (5), but in the design stages it can be quite successfully applied in the calculation of fuel consumption, especially in the comparative calculations (Zaabar, 2010).

Similar experiments were conducted on two articulated trucks KAMAZ-5320+SZAP-8350 with full weight 27420 kg on three types of roads: broken asphalt (f = 0.019), dirt road (f = 0.032), cobblestone (f = 0.027) and in the urban driving cycle (f = 0.02). During the experiments the average vehicle speed and fuel consumption were recorded. The results of experiment and calculation of fuel consumption for these conditions are given in Table 3. The following values were accepted μ_{eng} = 0.30; μ_p = 0.89; μ_v = 1; ρ = 0.98 kg/l.

Table 3 The results of measurement and calculation of the fuel consumption of the articulated truck KAMAZ-5320+SZAP-8350 with the gross weight 27420 kg on different types of roads

Parameter	Type of the road			
	Broken asphalt f = 0.019	Urban cycle f = 0.02	Cobblestone smooth f = 0.027	Soil f = 0.032
1. The mileage of the car No.1/No.2, km	16665/17838	3331/3404	6005/6019	4514/4500
2. The average speed, km/h	59/60	30.2/31	28.5/31	27.1/26.6
3. Average fuel consumption, l/100 km	49.5/51	67.6/69.3	69.0/69.0	81.3/86
4. Calculation by Eq. (5), l/100 km	48.6	51.1	69.0	81.8
5. The average error of calculation, %	3.2	25.3	0	2.2

As it is shown by the data from Table 3, the results of the calculation, except urban driving cycles, are in good agreement with the experimental data.

The deviation of the calculated fuel consumption from the experimental in the "urban driving cycle" by 25% is due to driving a car in the city, frequent stops and accelerations, downtime under the traffic light or because of traffic jams, expectations for passing other vehicles on the turns and forks. Taking into account this factor in the "urban driving cycle" it is recommended the calculated value of the fuel consumption to increase on average by 30% and determine the cost of fuel by the formula

$$S_f = 1.3VC_f. \tag{13}$$

In the formula (5) air resistance is taken into account by the empirical component (1.05 $\vartheta_f / \vartheta_n$ − 0.05). Formula does not take into account the value of streamlining and cross- sectional area of the vehicle, and the coefficient of road resistance is accepted regardless of vehicle speed. Modern cars have high speed, so in the presence of certain data, the formula (5) requires making adjustments.

To calculate the annual fuel consumption of the truck the new formula is offered, which excludes the aforementioned disadvantages, taking into account the main technical parameters of the car

$$\begin{aligned}Q_{year} &= 1.01K_{wint}K_{year}10^4\left(1+g_f\right)^t / \left(\rho H\mu_{eng}\mu_p\mu_v\right)\\ &\times(f_0\left(1+\vartheta_f^2/2000\right)\left[\beta\left(G_m+\gamma q\right)+\left(1-\beta\right)G_m\right]\\ &+0.05C_x\rho_{air}R\left(5/18\vartheta_f\right)^2),\end{aligned} \tag{14}$$

where

f_0 − is the coefficient of road resistance;

C_x − is the coefficient of aerodynamics of the car;

ρ_{air} − is the air density, kg/m^3;

R − is the cross-sectional area of the vehicle (articulated truck), m^2.

3 Conclusions

The proposed method was applied for the calculation of fuel consumption of truck tractors on the program "TransEuroTest". In the calculations the following conditions were taken: f_0 = 0.008; L = 1800 *km;* K_{wint} = 1; ρ = 0.98 kg/l; H = 42700000 J/kg; ρ_{air} = 1.24 kg/m^3.

The remaining vehicle parameters are given in Table 4.

Table 4 Technical parameters of truck tractors

Brand of tractor	ϑ_f, km/h	G, kg	R, m^2	C_x	μ_{eng}	μ_p	μ_v
Volvo	78.07	39300	7.5	0.55	0.38	0.92	1.0
MAN	79.32	39240	7.5	0.62	0.38	0.92	1.0
DAF	78.55	39280	7.5	0.62	0.38	0.92	1.0
Mercedes	77.00	38980	7.5	0.64	0.38	0.92	1.0
Scania	76.96	39140	7.5	0.58	0.37	0.91	1.0
Renault	75.53	38800	7.5	0.61	0.36	0.91	1.0
Foden	75.36	38880	7.5	0.59	0.36	0.90	1.0
Iveco	77.33	39080	7.5	0.62	0.36	0.91	1.0

The results of the calculation of total fuel consumption (Q), fuel consumption for 100 km (Q_{100}) and the deviation of the calculations relative to experimental data (δ) are given in Table 5.

Table 5 The results of calculations of fuel consumption of truck tractors, participants "TransEuroTest" (mileage 1800 km)

Brand of tractor	Q, l	Q_{100}, l/100 km		δ, %
	Due to (14)	Due to (14)	The experimental value	Formulas (14)
Volvo	659.2	36.62	36.67	-0.12
MAN	686.8	38.15	38.08	0.19
DAF	681.6	37.86	37.76	0.28
Mercedes	671.6	37.31	37.29	0.06
Scania	682.7	37.92	37.89	0.10
Renault	694.6	38.59	38.53	0.16
Foden	696.7	38.71	38.72	-0.04
Iveco	715.0	39.72	39.78	-0.14
The average value of formula error				0.06

As a result of comparison of calculations by the proposed formula with test results of 8 tractors on the program "TransEuroTest" (Lapshin, 2000) the following conclusion was obtained: Eq. (14) gives the average value of formula error regarding the experimental data of 0.06%.

The proposed formula is recommended for use to transport companies to calculate annual fuel consumption. The values of the parameters used in the proposed formula can be found in automotive manuals. Formula (14) allows to determine the fuel consumption of a vehicle more precisely. Fig. 1 shows the average fuel consumption of tractors at an average speed.

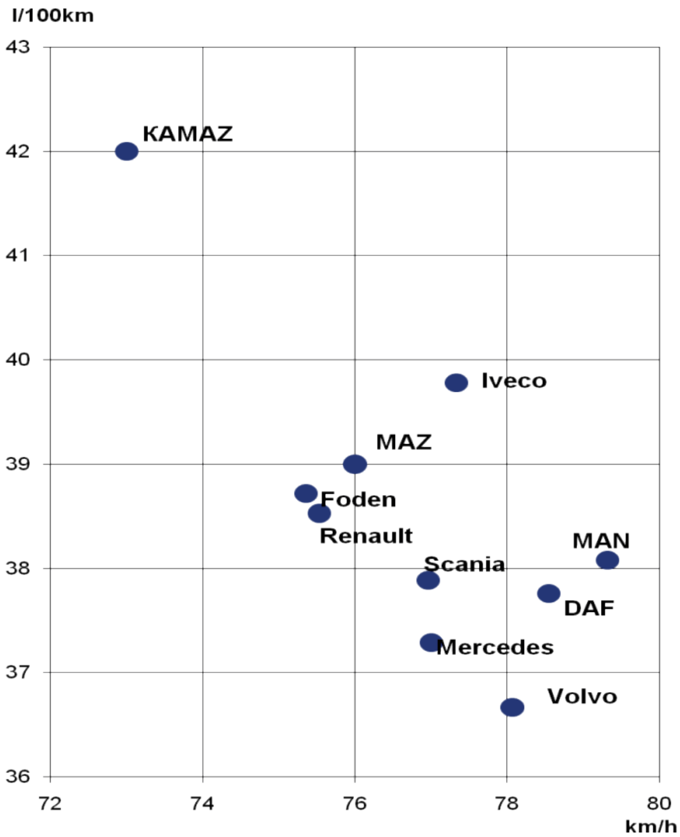

Fig. 1 The average fuel consumption of tractors at an average speed

The proposed formulas for calculating costs allow us to compare fuel consumption of different vehicles easily. The formula can also be used when evaluating the effect of vehicle weight on fuel consumption, which is impossible according to the well-known formulas. Most importantly, perhaps, that the proposed formulas are derived based on physical phenomena occurring during truck operation, allowing us to calculate cost of operation on the fuel more accurately.

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