Rated definition of daily fuel consumption of a city shuttle bus

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Abstract. Rated definition of fuel consumption by vehicles becomes the new direction of improvement of transportation processes. Calculations of daily fuel consumption by bus PAZ with the diesel engine used on city routes of Nizhny Novgorod with use of specifications of a definition technique of specific fuel consumption depending on extent application of engine power are executed. Results are compared with the existing normative indicators.

The specifications [1] made concerning a method of calculation of fuel consumption of the moving wheel car allow to calculate such useful properties of vehicles as daily fuel consumption on a specific route of the movement and also to make impact assessment on some factors, for example, for the purpose of searching ways of efficiency increase by using city buses.

For the theoretical analysis we will consider a real situation with shuttle buses of middle class buses PAZ-3204 with Cummins diesel engines which are widely used in Nizhny Novgorod. Technical characteristics of these cars are presented in table 1 [2]. The average daily run of such moving buses in city conditions makes 240 km, i.e. if the one way route length equals 20 km, the bus makes 12 trips per day from one final stop to another.

Table 1. Technical characteristics of the bus PAZ-3204 equipped the Cummins engine

| Parameter                                      | Value         |
|-----------------------------------------------|---------------|
| Mass of the equipped bus, kg                  | 5055          |
| Width-height, m                               | 2,41 x 2,88   |
| Maximum engine power (kW)                     | 104           |
| Angular speed of the crankshaft (rad / sec)   | 272           |
| Maximum engine torque (N*m)                   | 502           |
| Angular speed of the crankshaft (rad / sec)   | 136-178       |
| Gearbox ratios:                                |               |
| 4,65; 2,6; 1,53; 1,0; 0,77.                   |               |
| Main gear ratio:                               | 4,55          |
| Streamlining coefficient                      | 0,75          |
| Tyres                                         | 245/70R19,5   |
| Control fuel consumption, l / 100 km          | 16,3          |
| (at a speed of 60 km/h)                       |               |

For calculations of traveling fuel consumption of the moving bus with use of the known formulas of the theory of the cars [1, 5] it is necessary to know specific fuel consumption at maximum power $g_{eq}$ of Cummins engines. In this case quite correct result can be received on the basis of trial operation of completely loaded cars "Gazelle Next" equipped with Cummins diesel engines. It is known that with traveling speed of 60 km/h on 4th (direct) gear control fuel consumption was 8,5 l/100 km, at speed of 80 km/h it was already 10,3 l/100 km. These data in combination with technical characteristics of the specified cars allow to determine $g_{eq}$ in accordance with the mentioned formulas, and the obtained rated result ($g_{eq} = 227,5 \pm 0,5$ g/kW.h) is almost
identical to both options of the movement which affirms its reliability. In favor of such conclusion also calculation of \( g_{ref} \) proceeding of control fuel consumption (see table 1) the bus PAZ-3204 testifies.

One of the routes analyzed in this article has 16 stops. Therefore, for one trip along the route a driver carries out accelerations from zero speed to admissible 60 km/h in city conditions with gear shift use at least 15 times. At the same time, as observations showed, drivers use the first gear for start-off from the place very seldom. Rather high torsion torque of the diesel allows to start from the second gear. It is confirmed also by dynamic characteristics of the car which testify that the maximum ability rating on the second gear (a gear ratio 2,6), equals 0,18-0,19 when loading the bus by passengers up to 60-75%, it allows to make dispersal from the place with acceleration up to 1,5-1,7 ms\(^{-2}\). For 12 daily trips around the specified route of such start-off from the place at least 180 movements with acceleration on the third and fourth gears will be made.

The mass of the moving bus constantly changes because of passengers getting in and out at stops. In calculations it is necessary to operate with some average value. During its movement on a route average statistical data of changing passengers number inside the bus (figure 1) on this specific route allow to define average bus loading. From the obtained data it turns out that the average number of passengers in \( n_{tr} \), traveling by this bus route at approximately identical run between stops can be accepted as equal 19. Therefore the average full mass \( m_{fin} \) of the bus with passengers and the driver is equal

\[
m_{fin} = m_o + m_p (n_{tr}+1) = 5055 \text{ kg} + 68\times20 \text{ kg} = 6415 \text{ kg},
\]

where \( m_o \) – mass of the equipped bus, kg; \( m_p \) – mass of a passenger (68 kg [3]).

![Figure 1](image.jpg)

**Figure 1.** Change of the passenger number inside of the bus in the process of the movement on a route from an initial stop to the final one.

The first stage of acceleration of the bus from the place begins with preliminary promotion of an engine flywheel to angular speed 170-190 s\(^{-1}\) and the controlled driver of a clutch slip by the included second gear in a gearbox. The stage lasts 1,0-1,5 s and continues due to inertia of a flywheel acceleration of the car to the speed of 4 ms\(^{-1}\) (14 km/h) at negligible fuel consumption. Because of the fact that time of 2,0-2,5 s is spent for increase due to the additional fuel supply of rotational speed of the engine crankshaft to 200-210 s\(^{-1}\) and the corresponding increase in rotational speed of the driving wheels connected to its transmission (the clutch is in work!), then as the a result the car acceleration of at least 1,2 ms\(^{-2}\) and the speed of 7 ms\(^{-1}\) (25 km/h) is provided. At 180 such stages of working shift the bus will run \( S_2 = (2\times1,5+5,5 \times 2,5) 180 \text{ m} = 3 \text{ km} \), having spent such fuel quantity which is given in the calculation. The average power necessary for driving wheels during the process of a speed set on the second gear at the same time will be

\[
P_2 = m_{fin} g f V_{a2} + m_{fin} a_{a2} \delta_{a2} V_{a2} = 6415\times9,81\times0,012\times5,5 + 6415\times1,2\times1,41\times5,5 = 63,8 \text{ kW},
\]

where \( g \) – acceleration of gravity; \( f = 0,012 \) – rolling resistance coefficient; \( V_{a2} \) – the average speed of the bus at acceleration on the 2nd gear; \( a_{a2} \) – acceleration on the 2nd gear; \( \delta_{a2} \) – coefficient of accounting of the rotating masses on the 2nd gear.
Further at speed of 7 ms\(^{-1}\) there is a switching to the third gear (duration of switching \(t_1 = 1\) s), at the same time the way passed by the bus by inertia during a day will be defined by expression of \(S_3 = 7 \cdot 180\) m = 1,3 km.

The following stage is acceleration on the third gear. The bus engine and transmission provide acceleration \(a_3 = 0,8\) ms\(^{-2}\). Average speed at the stage \(V_3\) equals 9,5 ms\(^{-1}\), acceleration time to the speed of 12 ms\(^{-1}\) (\(= 43\) km/h) \(t_{a3} = 6,25\) s, therefore the way passed by bus on the 3rd gear during the working shift will make \(S_3 = 9,5\cdot6,25\cdot180\) m = 10,7 km. So, the average power necessary for driving wheels on the third gear will be

\[
P_3 = m_{m} g f V_3^3 + m_{m} a_3 \delta_3 V_3 + W_{sf} (V_3)^3 = 6415\cdot9,81\cdot0,012\cdot9,5 + 6415\cdot0,8\cdot1,16\cdot9,5 + 2,89\cdot9,5^3 = 7174 W + 56555 W + 2479 W = 66,2 kW,
\]

where \(W_{sf} \) – streamlining factor of the bus PAZ-3204 (\(W_{sf} = 2,89\) N.s\(^{2}\)m\(^{-3}\)).

At first there is switching to the 4-th gear before the acceleration stage. With duration of process of switching about 1 sec the way passed by bus by inertia on this mode for daily working shift will be defined by

\[
P_4 = m_{m} g f V_4^3 + m_{m} a_4 \delta_4 V_4 + W_{sf} (V_4)^3 = 6415\cdot9,81\cdot0,012\cdot14,75 + 6415\cdot0,4\cdot1,05\cdot14,75 + 2,89\cdot14,75^3 = 11740 W + 38670 W + 8540 W = 58,9 kW.
\]

Having reached maximum speed of 60 km/h permissible in the city, the bus has to continue to move on the fourth gear with constant speed. At the same time the necessity for the power driven to the leading wheels decrease significantly. It is defined by expression

\[
P_{const} = m_{m} g f V_{4}^{max} + W_{sf} (V_{4}^{max})^3 = 6415\cdot9,81\cdot0,013\cdot14,75 + 2,89\cdot16,7^3 = 27,16 kW.
\]

The track length, passed by the bus during the working shift on the fourth gear with constant speed, represents the difference between the full daily run (240 km) and runs of \(S_4\) on three gears used for a speed set, runs of \(S_3\) and \(S_2\) by inertia at gear shifts and also \(S_b\) during the braking time by the engine about 100-120 m before each stop when fuel supply in cylinders of the engine is turned off. As a result it will make for the considered route

\[
S_{const} = 240 – S_b – S_2 – S_3 – S_4 = 240 km – 18 km – 1,3 km – 2,2 km – 3,0 km – 10,7 km – 30,4 km = 174,4 km.
\]

Fuel consumption [1, 5] is defined for all rated points of value \(E\) of ratio \(E = \omega_s / \omega_p\) and calculated extent of engine power use is \(\mathbf{H} = P_e / k_b \eta P_{e,acc}\) according to the analytical method of definition of the wheel car. As previously reported we use \(\omega_s\) and \(P_{e,acc}\) corresponding to average speed of the bus at the considered stage (see table 2). The obtained values \(E\) allow to calculate coefficient \(K_E\) by means of the expression given in literature [1, 5]. Respectively, the obtained values \(\mathbf{H}\) allow to define \(K_H\) coefficient by the adjusting polynom [4, 5] removed earlier. As a result there is a possibility of calculation of specific fuel consumption \(g_e\) for each specific mode of the bus movement on a route (table 2).

**Table 2.** Results of calculation of daily fuel consumption of the shuttle bus PAZ-3204, equipped with Cummins engine at the passable traffic circuit of 240 km of and 180 stops during the working shift

| Parameter | Acceleration on the 2nd gear | Acceleration on the 3rd gear | Acceleration on the 4th gear | Motion on the 4th gear with \(V_{const} = 60\) km/h |
|-----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------------------------|
| \(\omega_{on}, c^1\) | 165 | 167 | 165 | 192 |
| \(E\) | 0,61 | 0,615 | 0,61 | 0,71 |
| \(K_E\) | 0,956 | 0,956 | 0,956 | 0,955 |
| \(\mathbf{H}\) | 0,88 | 0,91 | 0,775 | 0,34 |
| \(K_H\) | 0,924 | 0,937 | 0,931 | 1,059 |
| \(g_e, g/kWh\) | 201,4 | 204,2 | 203,1 | 230,6 |
For the considered situation it will be transformed in each of the considered stages. For this purpose it is possible to use expression (1) which is a little transformed in comparison with the initial one \([1, 5]\). For the considered situation it will be transformed in

\[
Q_s = g_e (P_{w} + P_{w2}) S_i / 3600 k_5 \rho V \eta_f ,
\]

where \(S_i / 100\) is the relative size of the way passed at the corresponding stage of the movement of the bus during the working shift (12 trips along a route).

Apparent from table 2, rated sizes of fuel consumption at separate stages turned out as such: \(Q_{s1} = 2,3 \text{ l} / \text{km}\), \(Q_{s2} = 6,0 \text{ l} / \text{km}\), \(Q_{s3} = 9,5 \text{ l} / \text{km}\), \(Q_{s4} = 24,5 \text{ l}\). Total daily fuel consumption by the bus on the specified route is made 42,3 l.

| Stage | Consumption, l/km | 2,3 | 6,0 | 9,5 | 24,5 | Qs, l |
|-------|------------------|-----|-----|-----|------|-------|
|       |                  |     |     |     |      |       |

With observance of the technique algorithm given here calculation of daily fuel consumption of the moving bus PAZ-3204 on the same route and with respect to the same of acceleration dynamics at stages is made, but at 30 stops (360 stops for a full working shift) this situation is better that corresponds to the real situation of the movement in city streets. Fuel consumption on stages were distributed as follows: \(Q_{s1} = 3,8 \text{ l} / \text{km}\), \(Q_{s2} = 11,8 \text{ l} / \text{km}\), \(Q_{s3} = 18,9 \text{ l} / \text{km}\), \(Q_{s4} = 50,1 \text{ l}\). Total daily fuel consumption made 50,1 l.

We will compare the obtained rated results with the real operation data of this bus models. So, according to poll of drivers in the Nizhny Novgorod transport LLC “Football”, the average value of fuel consumption at a daily run of 240 km on PAZ-3204 buses during the spring and autumn period of their operation is 45 ± 3 l. The obtained average calculated value (46,2 ± 3,9 l) gives an error of average size about 2,5% and this mistake takes into account the maximum dispersion of 11%. Therefore, the developed technique is quite applicable for practical purposes, in particular, for studying and the analysis of the specific operational problems connected with rationing of fuel consumption by wheel cars.

So, in actual practice drivers of shuttle buses are forced to stop at intersections and at traffic lights several times in addition to the stops planned on a route. The calculations which are carried out in this section show that each stop of the PAZ-3204 bus demands an additional expense about 0,03-0,05 l of fuel on the subsequent accelerations of the bus till the rated speed of the movement. Therefore for decrease in fuel consumption and increase in efficiency of city buses usage it is necessary to reduce quantity of unplanned stops. It depends to a large extent on the level of the organization of the movement in city streets and also on the ability of drivers to analyze the situation on the road quickly, in advance to foresee traffic light signals, and to able to apply actions for management of traffic flows like "green wave".

Also smoother accelerations of the bus from a stop with restriction of the maximum turns of the engine at level of 1700-1900 RPM and use of overdrive gear at the movement with constant speed till the rated speed of 50-60 km/h on direct gear is achieved through influence of these factors as calculations show, will affect fuel consumption reduction less significantly.

It should be noted that the important factor influencing fuel consumption is the maximum speed gathered by the city bus at the movement on a route. This conclusion is well confirmed by the example of calculation of daily fuel consumption for the bus PAZ-3204 used for public conveyances in Nizhny Novgorod as the share taxi route No. 40.

Route length is 24 km, it contains 44 planned stops. The analysis of traffic conditions on a route showed that in each run the driver is forced to make about 25-26 more necessary stops because of need of journey of a non-regulated intersection or a red signal of the traffic light. Therefore the total number of stops is calculated as equal 70. Thus at a daily run of 240 km the bus makes 10 runs, during the whole working day, i.e. the total number of stops for the working shift equals 700. At the same time the average size of a run between stops will be only 240/700 = 0,343 km. Therefore in most cases achievement of maximum speed of the movement of 60 km/h (16,7 ms\(^{-1}\)) which demands about 240-250 m for acceleration of the bus after a stop becomes not rational as right after it on the remained 100 meters it will be necessary to reduce the gained speed.

The obtained \(g_e\) values allow to pass to calculation of fuel consumption by this bus at the movement on each of the considered stages. For this purpose it is possible to use expression (1) which is a little transformed in comparison with the initial one [1, 5]. For the considered situation it will be transformed in

\[
Q_s = g_e (P_{w} + P_{w2}) S_i / 3600 k_5 \rho V \eta_f ,
\]
Observations showed that on a route No. 40 drivers are most often limited to a maximum speed set of 50-55 km/h (13,9-15,3 ms⁻¹). The average number of passengers inside the bus during the working shift insignificantly differs from the value accepted in the previous calculations - 19 people.

| Parameter | Acceleration on the 2nd gear | Acceleration on the 3rd gear | Acceleration on the 4th gear | Motion on the 4th gear with V_constant = 50 km/h |
|-----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------------------------|
| ω_eср, c⁻¹ | 187                         | 167                         | 150                         | 161                                           |
| E         | 0,69                        | 0,615                       | 0,55                        | 0,59                                          |
| K_E       | 0,954                       | 0,956                       | 0,96                        | 0,959                                         |
| H         | 0,84                        | 0,91                        | 0,76                        | 0,27                                          |
| K_H       | 0,926                       | 0,937                       | 0,933                       | 1,19                                          |
| g_e, r/kW.h | 201,6                      | 203,8                       | 204,2                       | 260,2                                         |
| Q_d, l    | 3,6                         | 23,1                        | 13,9                        | 6,5                                           |
| Consumption, l/km | 0,79                      | 0,56                        | 0,31                        | 0,14                                          |
| Q_dΣ, l   | 47,1                        |                             |                             |                                               |

Results of table 3 correspond to the situation when the bus moved on the fourth (direct) gear with the maximum speed of 50 km/h. The possible option when the bus picked up maximum speed of 60 km/h for 14% of sites between the next stops gathered was also analyzed (taking into account the fact that real availability of several sites between stops is up to 1,0-1,5 km long). In this case total daily fuel consumption is made as 48,9 l.

On the analyzed route there is a sudden abrupt (α = 6%) rise which length is about 1 km. Calculation showed that taking into account that on the return run the bus moves already on descent, and the engine works as a motor without consumption of diesel fuel, this factor will affect a total daily expense slightly (increase in rated size of a daily fuel consumption is on 0,3-0,5 l).

In conclusion it is said that rated definition consideration of fuel consumption by wheel cars is necessary to pay attention to that fact that indicators of specific fuel consumptions on 1 km of the passable way (see table 2 and table 3) in both in detail considered rated cases were on the 3rd and 4th gears identical, and on the 2nd gear they differ for only 2,5%. It is clear that the rated modes of the movement of the bus were chosen close to optimum.

Comparison of the obtained rated data with normative indicators of fuel consumption by bus PAZ-3204 with the Cummins B3.9 140 diesel engine in all considered cases appears not in favor of the Russian standard methodology of rationing of expenses of automobile kinds of fuel [6]. So, usually used when determining a standard consumption of fuel by the car without technological work (for buses – without fuel expenses on operation of the independent heater) the formula looks like:

\[ Q_{sn} = 0,01 \cdot H_f \cdot S \cdot [1 + 0,01(D)] \]  \( \text{(2)} \)

where \( H_f \) – the basic (linear) consumption rate of fuel for the specific vehicle, l/100 km; \( S \) – vehicle mileage, km; \( D \) – the sum of the regulated extra charges for features of operation, age of the vehicle, an operation season, etc., %.

For Nizhny Novgorod city shuttle bus route No. 40, considered in this research work \( H_f = 23,7 \) l/100 km [6], \( S = 240 \) km, \( D_1 = 25\% \) (the movement in city streets with the population about 1,5 million people, in summertime, the bus passed a running in and its age is less than 5 years); \( D_2 = 10\% \) (frequent technology stops of the vehicle) [6]. Substitution of these values in formula (2) yields such result

\[ Q_{sn} = 0,01 \cdot 23,7 \cdot 240 \cdot [1 + 0,01 \cdot (25+10)] = 76,8 \text{ l}. \]

The received value demonstrates that the normative size of fuel consumption by the city shuttle bus (76,8 l) with daily run 240 km practically by one and a half times exceeds the value defined by the technique of rated determination of daily fuel consumption by the same bus presented in article (47,1+ + 0,5 = 47,6 l –
taking into account additional costs of overcoming kilometer rise, fivefold during working shift) at a similar run. It should be noted that similar overestimate is typical for any vehicle used in Russia. It is confirmed by the numerous special researches conducted at Motor transport department of NSTU n. a. R.E. Alekseev [7]. For example this fact is confirmed by the example of cargo road trains in the thesis was is successfully defended [8].

The specified overestimated expenses of automobile fuels by the standard rationing technique in Russia, their difference from real values significantly reduce volumes of the taxes to the budget as the considerable part of profit of the auto enterprises is taken away "in a shadow". Besides, conditions for artificial overestimate of cost value of automobile transportations, expenses on fuel as a part of which make at least 30%, are created.

Conclusion: the standard technique of fuel consumption rationing on the motor transport needs to be subjected to essential changing, and it has to be made it on the methodology basis of the researches provided in this article and in some other scientific researches [1, 4, 5, 8].

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