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Mathematical Modeling and Computational Study of a Passenger Car Dynamics During Acceleration

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Abstract

A mathematical model of a passenger car dynamics during acceleration is proposed. The model takes into account the parameters of the car and engine, gear shift mode, external conditions (parameters of the road surface, road slope, gear shift time). As a result of the calculation for the ZAZ-Sens car, the loads that arise in the drive of the car were analyzed. The time for which the car accelerates from 0 to 100 km/h has been determined. The influence of vehicle mass, engine nominal power, gear shift mode, wheel radius, vehicle height, aerodynamic drag coefficient on the dynamics of vehicle acceleration has been analyzed. It is shown that the mass of the vehicle, the rated power of the engine and shifting gear time affect the acceleration dynamics to the greatest extent. The influence of other parameters is not so significant. The explanation of the obtained results is given.
KEY WORDS: *vehicle dynamics; mathematical modelling; drive unit; car parameters*

1. Introduction

One of the important parameters characterizing a vehicle dynamics is the acceleration time from 0 to 100 km/h. The comfort of driving a car, its commercial qualities depend on this parameter, therefore, improving the dynamic properties is one of the key tasks when designing a car.

The dynamics of a car depends on many parameters - the maximum power of the internal combustion engine, the weight of the car, the parameters of the gearbox, the frontal area of the car and others. The experimental study of the dynamics is complicated by the high labor intensity and cost of testing. It is rational to conduct a computational study using adequate mathematical models.

Currently, a number of detailed mathematical models describing vehicle dynamics have been proposed, for example [1-4]. In these models, the car is presented as an oscillating system. The rolling of the wheel on uneven and smooth surfaces is described in detail, the inertial and elastic characteristics of the moving parts of the engine, transmission and wheels are taken into account. These models are characterized by the complexity of validation and require setting a number of empirical coefficients based on the results of experimental studies. In addition, there is very little information in the literature on the use of such models in tasks of car parameters optimization.

In some cases, for example, when creating a draft design of a car, preliminary study of the powertrain design, it is rational to use simple but at the same time sufficiently reliable mathematical models [5-7]. A fairly popular model in Eastern Europe countries is the model of Chudakov and Yakovlev, detailed in [5]. This model allows determining acceleration and path of the car and based on the dynamic factor calculation. In turn, the dynamic factor depends on the forces acting on the car during its movement. However, this model doesn't take into account the influence of the gear shift time on the dynamics of car acceleration. Existing methods of modeling the process of shifting gears take into account the processes of interaction of leading and led friction elements of the transmission. However, their use at the initial stage of design, when kinematic and mass parameters of the transmission parts are unknown is problematic.

The purpose of the work is to create a simple mathematical model of the car acceleration dynamics and to perform a computational research of car parameters influence on the acceleration process.

2. Vehicle Parameters and Driving Conditions

The ZAZ-Sens car with the MeMZ-307 engine was selected as the object of the research (Table).

Table

ZAZ-Sens car parameters

Parameter	Parameter value	Parameter	Parameter value
Vehicle mass m, kg	1100	Piston stroke S, m	0.0735
Static radius of the tyre r_{st}, m	0.285	Compression ratio ε	9.8
Vehicle height B_r, m	1.432	Engine nominal power N_n, kW	50
Vehicle width H_r, m	1.678	Engine nominal speed n_n, rpm	5400
Frontal area filling factor α_A	0.78	Transmission efficiency η_{tr}	0.92
Engine displacement, V_h, l	1.3	Gear ratios: u_{k1}; u_{k2}; u_{k3}; u_{k4}; u_{k5}	3.454; 2.056; 1.333; 0.969; 0.828
Cylinder diameter D, m	0.075	Final drive ratio u_0	4.13

3. Calculation Method

The developed mathematical model is based on the method of Chudakov and Yakovlev. The speed interval of a car from 0 to 100 km/h was divided into small sections with duration of 1 km/h. It is considered that at each section the car is moved with constant acceleration. Thus, knowing the speed at the beginning of the section and the average acceleration in the calculated interval, one can determine the speed at the end of the section.

The main parameter that determines the current value of vehicle acceleration is the dynamic factor (sometimes it is called ‘performance’ factor) D, which depends on the traction force, air resistance force and vehicle weight. Thus, the task of the study was to calculate parameters determining the dynamic factor and acceleration of the vehicle.

It is shown that the basic method doesn’t take into account the influence of gear shifting time on the car acceleration dynamics. The authors proposed to determine the acceleration time Δt from speed v_1 to speed v_2 when shifting gears by the following method. Time Δt is divided into two intervals (Fig. 1):

$$\Delta t = \Delta t_1 + \Delta t_2 ,$$

where Δt_1 – gear shifting time; Δt_2 – acceleration time from speed v_1 to speed v_2.

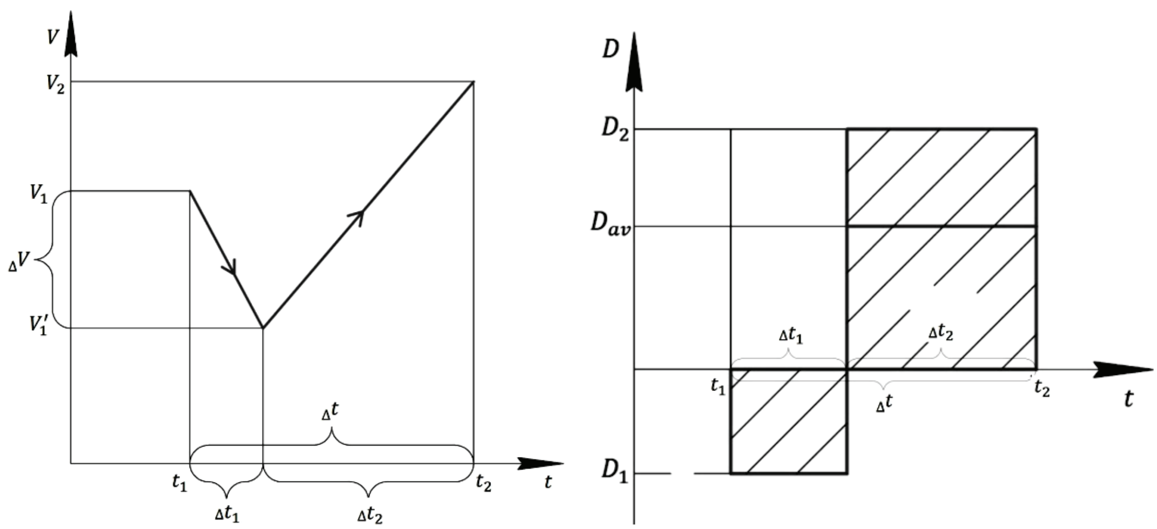

Fig. 1 Scheme for determining the acceleration time of a car when shifting gears

The time Δt_1 depends on the driver's qualification and can vary from 0.2 to 3 s. During the time Δt_1 the speed of the car decreases by the value of Δv and at the end of the first interval reaches the value $v_1^{'} = v_1 - \Delta v$.

When shifting gears, the car moves by inertia, and the traction force F_{t1} = 0. Accordingly, the dynamic factor during the interval Δt_1:

$$D_1 = -\frac{F_{v1}}{G} , \qquad (1)$$

where F_{v1} – aerodynamic drag; G – vehicle weight.

The dynamic factor D_1 determines the acceleration of the car j_1 in the interval Δt_1.

To simplify the calculations, it is assumed that aerodynamic drag F_{v1} when changing gears is considered constant and corresponds to the speed of the previous gear. In this case, the acceleration j_1 is considered to be constant and the reduction in speed when shifting gears will be $\Delta v = j_1 \cdot \Delta t_1$.

During the second interval, after clutching the crankshaft with the engine transmission traction force F_{t2}, dynamic factor D_2, acceleration j_2 and acceleration time Δt_2 from speed v_1 to speed v_2 are calculated by the formulas of the basic method for a car movement with a certain gear ratio.

The average dynamic factor in the calculated interval:

$$D_{av} = \frac{D_1 \cdot \Delta t_1 + D_2 \cdot \Delta t_2}{\Delta t_1 + \Delta t_2}. \tag{2}$$

The average speed in the calculated interval

$$v_{av} = \frac{\left(v_1 + v_1'\right) \cdot \Delta t_1 + \left(v_2 + v_1'\right) \cdot \Delta t_2}{2}. \tag{3}$$

The traction force depends on the engine power. When the car accelerates in order to achieve maximum speed, the accelerator pedal is pressed all the way, therefore, the engine operates with maximum power according to the external speed characteristic. The operating engine power can be determined by the empirical Leiderman's formula:

$$P = P_n \cdot \left[A_1 \cdot \frac{n}{n_n} + A_2 \cdot \left(\frac{n}{n_n}\right)^2 - \left(\frac{n}{n_n}\right)^3 \right], \tag{4}$$

where P_n – nominal power; A_1, A_2 – empirical coefficients. For the MeMZ-307 engine we can take $A_1 = A_2 = 1$; n, n_n – operating and nominal engine speed.

Operating engine speed is determined by the vehicle speed, wheel sizes and transmission parameters

$$n = \frac{v \cdot u_k \cdot u_{pb} \cdot u_0}{0,377 \cdot r_{st}}, \tag{5}$$

where v – vehicle speed; u_k – operating value of the gear ratio; u_{pb} – transfer case ratio; u_0 – final drive ratio; r_{st} – static tyre radius.

The calculations were performed in the MATLAB program.

4. Analysis of Calculation Results

4.1. Loads in the Vehicle Drive During Acceleration

The results of calculating the forces in the car drive during acceleration are given in Fig. 2, engine parameters – in Fig. 3.

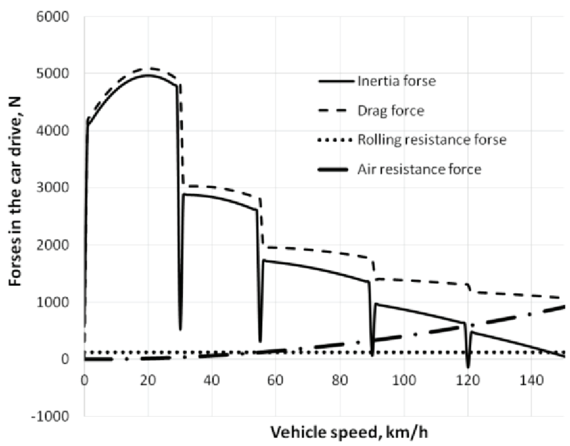

Fig. 2 Forces in the car drive during acceleration

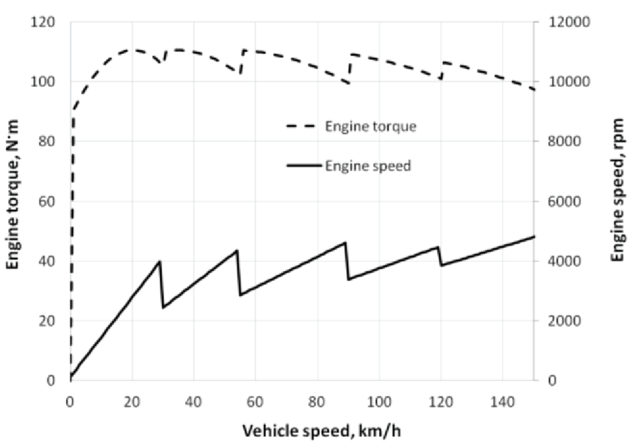

Fig. 3 Engine parameters

When calculating the gear shift time was set to 0.5 s. Switching from first to second gear was carried out when reaching a speed of 30 km/h, from second to third – when reaching a speed of 55 km/h, from third to fourth - when reaching a speed of 90 km/h, from fourth to fifth – when reaching speed of 120 km/h.

Fig. 3 shows that with the basic settings in each gear, the crankshaft speed during acceleration increases to values close to 4000 rpm. This provides a sufficiently large power, engine torque and traction on the wheels. This traction is spent mainly on overcoming the inertia force, which at the beginning of the car moving exceeds the rolling resistance and aerodynamic drag more than 50 times. As the speed of the car increases, the inertia force decreases and at a speed of 100 km/h it is only twice that of the other components of the load.

From Fig. 2 we can see that the aerodynamic drag grows in proportion to the square of the vehicle speed and at a speed of 100 km/h makes a significant contribution to the overall driving resistance. This force limits the maximum speed for the car, the calculated value of which is 155 km/h. The increase in speed can be achieved mainly by increasing the engine power.

The speed of 100 km/h is reached in 18.6 s (Fig. 4), which corresponds to the passport data of the ZAZ-Sens car and indicates the adequacy of the calculation method.

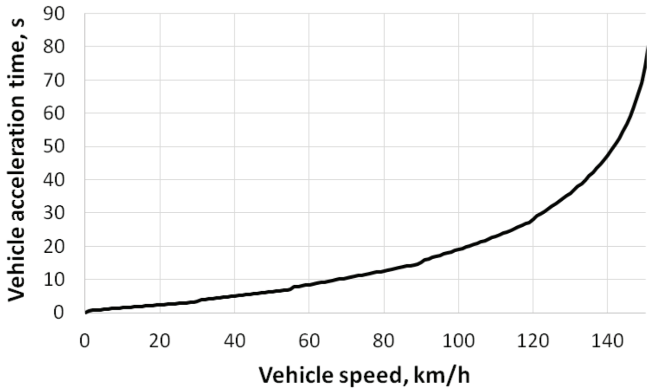

Fig. 4 Vehicle acceleration time

Thus, the developed mathematical model allows to research the performance of an engine and a vehicle during acceleration, determine the influence of car parameters on these processes and to carry out optimization studies.

4.2. Influence of Car Parameters on the Acceleration Dynamics

Using the mathematical model, the influence of the vehicle mass, static tyre radius, vehicle height, engine nominal power, drag coefficient, gear shift mode on the vehicle acceleration has been studied.

Basic set of parameters: vehicle weight – 1100 kg, static tyre radius – 0.285 m, vehicle height – 1.432 m, nominal engine power – 50 kW, drag coefficient – 0.3. Gear shift mode: the first gear is engaged when driving from 0 to 30 km/h, the second gear – from 30 to 55 km/h, the third gear – from 55 to 90 km/h, the fourth gear – from 90 to 120 km/h, the fifth gear – more than 120 km/h.

The nominal power of the engine was set in the range from 40 to 80 kW. Engines of such power can be installed without significant problems in the engine compartment of a ZAZ Sens car.

The car mass varied from 900 to 1400 kg. It was considered that the minimum mass according to the passport characteristics of 1100 kg can be reduced to 900 kg by using a plastic or aluminum lining of the body, replacing the cast-iron engine block with an aluminum alloy block. Maximum vehicle mass with full load - 1400 kg. It was left unchanged.

The static tyre radius varied from 0.24 to 0.33 m. Such tyres can be used without significant alterations to the car body.

According to [5] shifting gear speed varied from 0.5 to 3 s.

Drag coefficient was set in the range from 0.2 to 0.35. Such parameters have existing cars; therefore, they can be implemented on an experimental car.

When shifting gears, three variants were considered, which differ in the speed ranges of the vehicle when shifting. In addition to the basic one (called ‘Variant 2’), a Variant 1 was proposed when the first gear was engaged when driving from 0 to 20 km/h, the second - from 20 to 45 km/h, the third - from 45 to 70 km/h, the fourth - from 70 up to 100 km/h, the fifth - more than 100 km/h and the Variant 3 when the first gear is engaged when driving from 0 to 40 km/h, the second - from 40 to 65 km/h, the third - from 65 to 110 km/h, the fourth - from 110 to 140 km/h, the fifth - more than 140 km/h.

Influence of the ZAZ-Sens car parameters on the acceleration time from 0 to 100 km/h is shown in Fig. 5.

Analysis of the calculation results showed that the most significant influence on the acceleration time have the engine power, car mass and shifting gear speed. The effect of the vehicle weight and shifting gear speed on the acceleration time is linear. With a decrease in vehicle weight for every 100 kg, the acceleration time from 0 to 100 km/h decreases by 1.6 s. Increasing the gear shift speed for every 0.5 s reduces the acceleration time by 2 s.

The influence of the engine power on the acceleration time is nonlinear. An increase in the nominal engine power for every 10 kW leads to a decrease in the acceleration time by 1.6-5.3 s. Larger values refer to the low power range, lower values – to the relatively high power range.

The drag coefficient and vehicle height do not significantly affect engine acceleration. This is due to the fact that these parameters determine the drag force. However, at speeds up to 100 km/h, the specific contribution of the drag force to the total driving resistance to movement during acceleration is not significant. The main component of the total resistance is the inertial force.

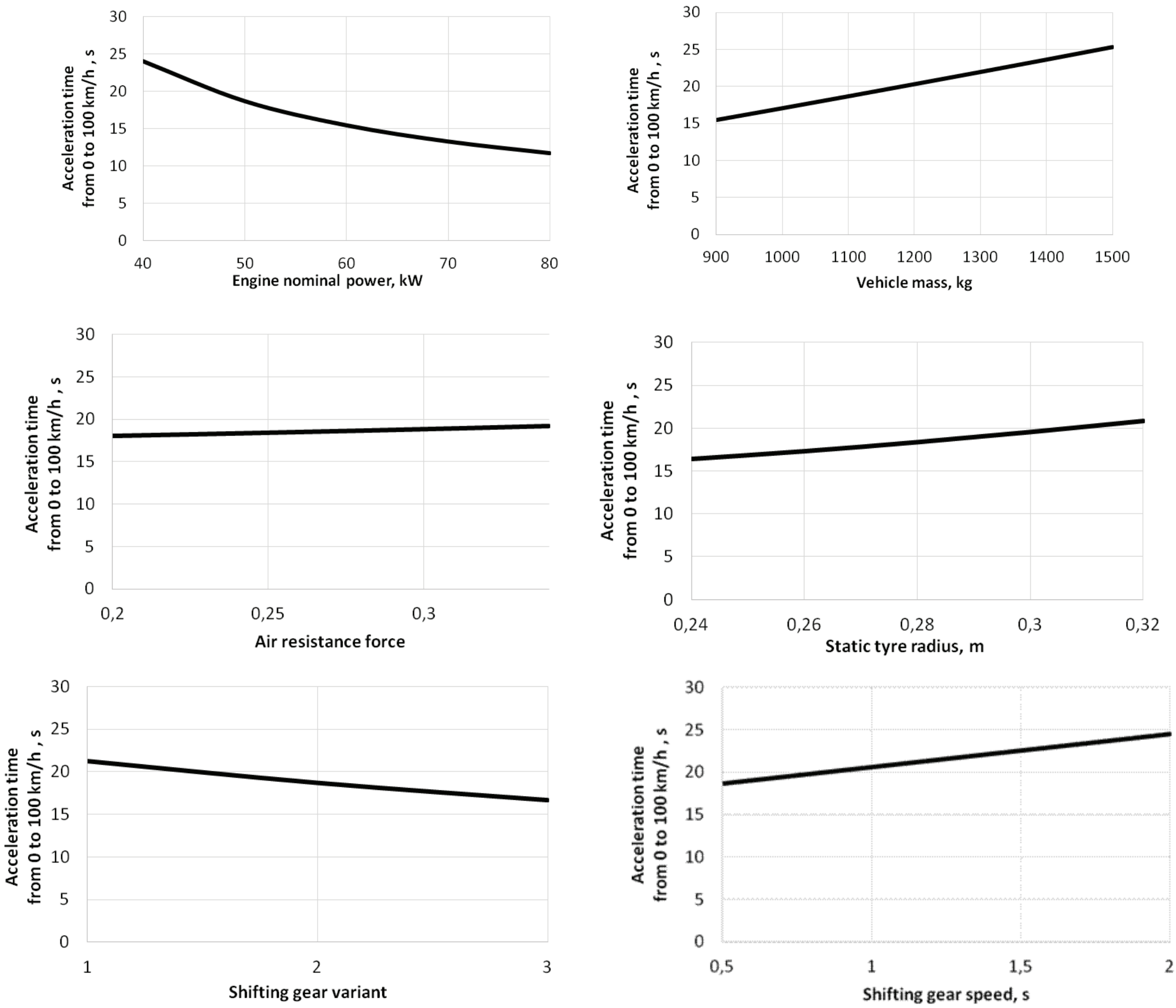

Fig. 5 Influence of the ZAZ-Sens car parameters on the acceleration time from 0 to 100 km/h

Fig. 5 shows that a decrease in the static tyre radius for each centimeter improves the acceleration time of the car by about 0.8 s. This is due to the fact that with a constant gear ratio, the engine runs at high speeds. This achieves high maximum power and tractive effort. However, it should be noted that this measure of improving acceleration time is undesirable, since simultaneously with a decrease in the size of the wheels, the wear of the protectors increases, the friction in the transmission increase, and, consequently, the fuel consumption increases and the reliability of the car decreases. In addition, the driving comfort is deteriorated due to increased vibration when driving on the road surface.

The way of shifting has a similar effect on the car acceleration. Later shifting leads to an increase in engine speed, power and traction. Accordingly, the acceleration time decreases.

Thus, the developed mathematical model allows determining the quantitative impact of changes in the parameters of an engine and a car on the dynamics of its acceleration, to choose the parameters of the vehicle at the stage of its design.

5. Conclusions

The paper presents the mathematical model of a car dynamics, which takes into account the impact on this process gear shifting speed. The model allows to research the performance of an engine and a vehicle during acceleration, determine the influence of car parameters on these processes and to carry out optimization studies.

Using this mathematical model, the influence of the ZAZ-Sens car parameters on the acceleration time from 0 to 100 km/h has been researched. It is shown that the mass of the vehicle, the rated power of the engine and shifting gear time affect the acceleration dynamics to the greatest extent. The influence of other parameters is not so significant. The explanation of the obtained results is given.

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