Method of ensuring the active and operational safety of a motor vehicle with a science-based choice of a tire profile family with regard to the characteristics changes of shock absorbers

I M Ryabov¹, A V Pozdeev¹, K V Chernyshov¹, S V Danilov², Sh M Mukhuchev³, Z K Omarova³ and M V Poluektov¹

¹Volgograd State Technical University, Volgograd, Russian Federation
²North Caucasus State Academy, Cherkessk, Russian Federation
³Makhachkala branch of Moscow Automobile and Road Construction State Technical University, Makhachkala, Russian Federation

E-mail: pozdeev.vstu@gmail.com

Abstract. This work contains a description and method of ensuring the active and operational safety of a motor vehicle with a science-based choice of the tire profile family with regard to the characteristics changes of shock absorbers. A specific example of the application of this method is given.

1. Introduction
Currently, the issue of road traffic injuries reduce in road transport is an acute problem. World statistics show that more people die in car accidents every year than in accidents on other types of transport. According to the United Nations, about 500 thousand people die in road accidents (RTA) every year, and about 10-15 million are injured. In the Russian Federation, the risk of human death per unit of transport work performed on road transport is 250 times higher than on rail transport. According to GIBDD, from 13 to 18% of road accidents caused by adverse road conditions, i.e. potted surface of roads in the Russian Federation. The statistics of road pavement defects on the federal highways of the Russian Federation shows that the share of vicious pave sections is 54%. The share of areas with deformed coating is 72%.

2. The problem of ensuring the active and operational safety of motor vehicles
The existing systems of active safety of a motor vehicle on vicious pave section of the road become ineffective because the wheels are detached from the road that impairs the vehicle steerability and braking properties of the motor vehicle. The effect of worn smooth shock absorbers (by 50%) on a braking path of motor vehicles equipped with anti-lock braking system (ABS) and without it, when driving on a dry, rough road at a speed of 80 km/h, is shown in Table 1 [1].
Comparison of data in Table 1 shows that the braking path of the motor vehicle on a dry, rough road with worn-out shock absorbers without ABS increases insignificantly (by 1.6 m), and with ABS it increases significantly (by 5.4 m). Thus, if the shock absorbers of a motor vehicle are worn out due to wheel break from the road than the electronic anti-lock braking system reduces its effectiveness on a rough road.

| Brake system of the motor vehicle | The braking path of vehicles, m |
|-----------------------------------|-------------------------------|
|                                   | New shock absorbers | Shock absorbers with wear of 50% |
| without ABS                       | 37.5               | 39.1 (+ 4.3%)          |
| with ABS                          | 38.2               | 43.6 (+ 14.1%)         |

Table 1. The braking path of vehicles equipped with ABS and without it on rough road at a speed of 80 km/h.

Such factors as stiffness and static deformation of tires also have a great influence on vibrations and motor vehicle wheels tearing off from the road. Since the elastic characteristic of the tire is close to linear, these indicators are related: the greater the stiffness, the less the static tire deformation. In a motor vehicle design and finishing, motor manufacturers develop for tire companies the technical design specification for new tires, which, in order to produce tires that meet the requirements specification, perform their approval-adapting to a specific car to improve its service properties. The tire adapting process takes about 3 years and is cost-consuming, therefore, to save time and resources on the tire adapting, it is necessary to develop a method of science-based choice of tire profile family accordingly the suspender element properties (elastic element and shock absorber) and the microprofile of roads (mean square roughness height) of the motor vehicle operation.

In addition, after some time of the motor vehicle operation, the tire tread wears out, that necessitates their change. For change, it is desirable to find exactly the same tires that were installed on the motor vehicle by its manufacturer, but it is difficult to find them, since their release is usually small. Therefore, motorists choose other tires, and often they choose well-advertised tires of a lower profile family and even ultra-low profile tires (family is below 40), which are suitable for load and speed indexes. However, low-profile and ultra-low-profile tires have greater stiffness, the large amplitudes of wheel vibrations from the impact of irregularities become more intense, and they also have a small static deflection (which is commensurate and even less than the height of the most likely roughness of asphaltic concrete road in the Russian Federation). Therefore, the time of wheels tearing off from the road increases, dramatically reduces the active motor vehicle safety. At high speed, the motor vehicle becomes like a lost control plane, since the control is lost, and it is impossible to stop quickly, that increases the risk of an emergency situation and RTA.

The problem of ensuring the active and operational safety of a motor vehicle is also related to the fact that for the service life of a motor vehicle its tires are changed several times, and the shock absorbers are changed, as a rule, less often. The average mileage of foreign-made motor vehicle tires and CIS member countries before tread wear is 40...60 thousand km [2], and the shock absorbers reach a critical resource threshold (shock absorber resistance forces decrease by 25%) after 60...80 thousand km [3, 4], it is therefore advisable to change them simultaneously. But it is not done, because in the GOST R 51709-2001 standard currently in force in the Russian Federation, which establishes requirements for the technical condition and methods of their checking when allowing motor vehicle to operate [5], as well as in the Technical Regulations of the Customs Union (ТР ТС 018/2011) “On the reliability of the wheeled vehicles” [6], there are no requirements for shock absorbers, suspension elements and tire height.

Thus, to ensure the active and operational safety of a motor vehicle, it is necessary to develop a method of tires selection according to stiffness (profile family) taking into account the shock absorbers characteristics. The method should ensure that there are no wheels tearing off from the road by the time of tires changing, even when the shock absorber reaches a critical resource threshold. To ensure
operational safety, it is necessary that when tires are changing, the motor vehicle shock absorbers have a reserve of resources to compensate for their wear.

3. A new method of ensuring the active and operational safety of a motor vehicle

For the development of the method as an assurance of active and operational safety, we will consider the absence of wheels tearing off from the supporting surface. The criterion of the wheel tearing off from the supporting surface will be taken the excess of the amplitude of the tire deformation of its static deformation under the downward force of $y_0$ per wheel:

$$y_0 \geq y_u.$$ (1)

Let us consider the theoretical method for their determination to establish the relationship between the parameters of tires and shock absorbers that satisfy the selected criterion. Taking into account the well-known assumptions [7-9], the oscillating system equivalent to the rear and front of the car will be represented by a single-support two-mass design scheme (Figure 1), the differential equations of motion of which are as follows [10]:

$$m_1 \ddot{z}_1 + k_1 (\dot{z}_1 - \dot{z}_2) + c_1 (z_1 - z_2) = 0;$$

$$m_2 \ddot{z}_2 + k_2 (\dot{z}_2 - \dot{q}) + c_2 (z_2 - q) - k_1 (\dot{z}_1 - \dot{z}_2) - c_1 (z_1 - z_2) = 0.$$ (2)

We divide the first and second equations by $m_1$ and $m_2$, respectively:

$$\ddot{z}_1 + \frac{k_1}{m_1} (\dot{z}_1 - \dot{z}_2) + \frac{c_1}{m_1} (z_1 - z_2) = 0;$$

$$\ddot{z}_2 + \frac{k_2}{m_2} (\dot{z}_2 - \dot{q}) + \frac{c_2}{m_2} (z_2 - q) - \frac{k_1}{m_2} (\dot{z}_1 - \dot{z}_2) - \frac{c_1}{m_2} (z_1 - z_2) = 0.$$ (3)

For this, with constant values of the sprung and unsprung masses, the maximum value of the strain amplitude of tires of different stiffness (at the second resonance) was determined. In the calculations, the stiffness of the tire from the following range was taken: 100, 200, 300, …, 1000 kN/m). On the diagram (Figure 2) the points were put corresponding to the obtained maximum values of the amplitude of the deformation of the tires, and connecting the points of the curve 1 was obtained. Then the value of the relative damp coefficient $\psi$ in the suspension was incrementally increased from the following range: 0.25, 0.3, 0.35, 0.5 and similarly the curves 2-5 were built. The amplitude of the equivalent harmonic roughness for the low-worn road $q_{01} = 10$ mm was taken, and the curves 1-5 were built on the left vertical scale. To take into account the developed methodology, more stringent operating conditions of the motor vehicle, for example, mainly on well-worn roads, which have the amplitude of the equivalent harmonic roughness $q_{02} = 20$ mm, were used.

Figure 1. The design scheme equivalent to the vehicle suspension bracket: $m_1$ – sprung mass; $m_2$ – unsprung mass; $c_1$ – spring stiffness; $c_2$ – tire stiffness; $k_1$ – damping ratio of the shock absorber; $k_2$ – damping ratio of the tire; $z_1$ – sprung mass displacement; $z_2$ – unsprung mass displacement; $q$ – kinematic perturbation of oscillations.
roughness of $q_{02} = 15$ mm (1.5 times more), the right vertical scale is built on the diagram, the values of which are 1.5 times more than the left scale. Then, in the diagram (Figure 2), we build the dependences of the change in static deformation on the stiffness of the tire. We assume that the static deformation of the tire $y_{st}$ varies inversely as its stiffness $c_2$ according to the equation:

$$y_{st} = \frac{(m_1 + m_2)g}{c_2},$$

where $g$ is the gravitational acceleration.

Figure 2. The dependences of the amplitude of tire deformation at the second resonance on the tire stiffness at different levels of damping $k$ and parameters: $m_1 = 1200$ kg, $m_2 = 120$ kg, $c_1 = 47374$ N/m ($\omega_01 = 2\pi$ rad/sec), amplitudes of equivalent harmonic roughness of $q_{01} = 10$ mm and $q_{02} = 15$ mm: 1 – $k = 3016$ N·sec/m ($\psi = 0.2$); 2 – $k = 3770$ N·sec/m ($\psi = 0.25$); 3 – $k = 4524$ N·sec/m ($\psi = 0.3$); 4 – $k = 5278$ N·sec/m ($\psi = 0.35$); 5 – $k = 7540$ N·sec/m ($\psi = 0.5$); 6 – static tire deformation on the left scale (for determining boundary stiffness of tire at an amplitude of an equivalent harmonic irregularity $q_{01} = 10$ mm, corresponding to low-worn road); 7 – static tire deformation on the right scale (for determining boundary stiffness of tire at an amplitude of an equivalent harmonic roughness of $q_{02} = 15$ mm, corresponding to well-worn road).

By equation (4), curves 6 and 7 are built for the left and right vertical scales, respectively. Curve 6 corresponds to a slightly worn asphalt concrete road (the amplitude is equivalent to harmonic roughness $q_{01} = 10$ mm (left scale)). Curve 7 corresponds to a worn asphalt concrete road (the amplitude of the equivalent harmonic roughness is $q_{02} = 15$ mm (right scale)). Dropping perpendiculars from the cross points $A_1$, $B_1$, $C_1$, $D_1$, $E_1$ and $A_2$, $B_2$, $C_2$, $D_2$, $E_2$ of the curves 6 and 7 with curves 1-5, the stiffness of the chosen tire is determined, when exceeded which there is the wheel tearing off on the roads with an amplitude equivalent harmonic roughness of $q_{01} = 10$ mm and $q_{02} = 15$ mm, respectively.

Thus, the diagram was obtained according to which, knowing the state of the shock absorbers (the relative attenuation vibrations coefficient $\psi$, which is determined in various ways, including on the special stands), it is possible to determine quickly the boundary stiffness of the tires to be chosen when their changing, ensuring the absence of the wheel tearing off from the road with different height of irregularities.

To determine the dependence of the tire stiffness on its family profile, we introduce a new indicator
"relative stiffness of the tire": 

\[ c_{rel} = \frac{c_{2\text{new}}}{c_{2\text{old}}} \]  

(5)

where \( c_{2\text{new}} \) is the stiffness of the new (selectable or selected for change) tire; \( c_{2\text{old}} \) is stiffness of the tire to be changed. Taking into account the fact that the static deformation of the tire is 10 ... 12% of the profile height [7], using formulas 4 and 5, we build a dependence showing an increase in the relative stiffness of tires of the lower family (65 ... 40) when they change tires of the 70 series currently prevalent (Figure 3). Analysis of Figure 3 shows that by reducing the family of changed tires from the 70th to the 40th, their stiffness increases 1.75 times exponentially.

![Figure 3](image)

**Figure 3.** The dependence showing the increase in the relative stiffness of the tires of the lower series (65-40) when replacing them with the tires of the 70 series (currently in use).

A graph similar to the graph in Figure 3, you can build for any tires family, it can immediately determine how many times will increase the stiffness of the tire. For example, when changing the 70 tires family on the 50 tires family, their stiffness will increase in 1.4 times.

For a more convenient and accurate finding of the boundary stiffness of the tire being changed in case of shock absorbers changing on motor vehicles with different stiffness of the elastic suspension element on the basis of a diagram (Figure 2), we will build a diagram (Figure 4).

This diagram shows the dependences of the tire stiffness, at which their tearing off from the road begins (at the second resonance) from the level of damping in the suspension at different stiffness of the elastic suspension element and the amplitude of the irregularities. Curves 1 and 3 are built for soft suspension. Curve 2 is constructed for a stiffer (2 times) suspension at an amplitude equivalent to the harmonic roughness is \( q_{01} = 10 \text{ mm} \).

4. Method application example

Task: to develop recommendations for a science-based choice of the replaceable tire profile family for a light motor vehicle with a soft suspension, operated on low-worn roads (Figure 4, curve 1) and tires having the stiffness of 400 kN/m (Figure 4, horizontal dashed line).

The following cases are possible.

Case 1. The car had shock absorbers providing \( \psi = 0.25 \), but by the time of change they were worn out and provide only \( \psi = 0.15 \).

Selection guideline of the tire change:
since curve 1 passes through point A (ψ = 0.15, c₂ = 400 kN/m), according to the safety conditions (non-tearing off wheels rolling), it is prohibited to put tires more non-flexible (lower family) than they were, but you can put the same and plan to change the shock absorbers;

- it is better to put softer tires of a larger family than they were, since with further wear and decrease in the effectiveness of the shock absorber, the tires that were put on the motor vehicle would be too non-flexible, the wheel tearing off would start and the safety of the motor vehicle would decrease.

Case 2. The car had high-quality shock absorbers, providing ψ = 0.25, which at the time of tire change almost did not wear out.

Selection guideline of the tire change:

- the value ψ = 0.25 on curve 1 corresponds to a tire stiffness of c₂ = 550 kN/m (point B), so when change, you can choose tires of a lower family (greater stiffness), preferably not more than 500 kN/m, so that the stock remains for wear of shock absorbers and it is necessary to monitor their condition;

- it is better to put the same tires of the same family when changing.

**Figure 4.** The dependence of the tire stiffness when the breakaway from the road starts in the second resonance, from damping in the suspension with different suspension stiffness and the height of irregularities with the following parameters: sprung mass m₁ = 1200 kg; unsprung mass m₂ = 120 kg; curve line 1 – for the amplitude of the equivalent harmonic roughness q₀₁ = 10 mm and stiffness of suspension: c₁ = 47374 N/m (ω₀₁ = 2π rad/sec, ν₀₁ = 1 Hz); curve line 2 – for the amplitude of the equivalent harmonic roughness q₀₁ = 10 mm and greater stiffness of suspension c₁ = 106592 N/m (ω₀₁ = 3π rad/sec, ν₀₁ = 1.5 Hz); curve line 3 is constructed for the same parameters as curve line 1, but for the amplitude of the equivalent harmonic roughness q₀₂ = 15 mm.

5. Conclusions
The criterion for ensuring the safety of the motor vehicle is chosen - the absence of the wheel tearing off from the road, which is determined by the excess of the dynamic deformations of the tire in the time of oscillation of its static deformation under the influence of the weight of the motor vehicle.

A new indicator “relative tire stiffness” has been proposed, which shows how many times the stiffness of a new tire is greater than old tire stiffness when it is changed.

A specific example of the application of method of improvement motor vehicle safety through a science-based choice of tire profile family when changing them is given.

Thus, in the article, based on the criterion of non-separable rolling of wheels, the method was developed to ensure the active and operational safety of a motor vehicle by science-based choice of tire profile family with regard to the characteristics changes of shock absorbers and the example of its practical application is given.

References
[1] Evzovich V E, Reibman P G 2010 Car tires, wheels and rims (Moscow, Avtopolis-plus) 144 p
[2] RD 3112199-1085-02 2002 Temporary norms of the operational mileage of the tires of vehicles (Moscow, Ministry of Transport of the Russian Federation)
[3] Ryabov I M , Chernyshov K V , Gasanov M M , Mukhuchev Sh M 2014 On the problem of safety in the operation of cars with faulty shock absorbers News of Volgograd State Technical University [Izvestiya Volgogradskogo gosudarstvennogo tehnichestkogo universiteta – in Russian] 9-19 (146) 103–106
[4] Savelyev V V 2005 Improvement of car service by intensification of preventive strategy: On the example of front-wheel drive cars VAZ: the abstract of the dissertation of Candidate of technical sciences (Volgograd, Volgograd State Technical University) 163 p
[5] GOST R 51709-2001 2010 Motor vehicles. Safety requirements for the technical condition and verification methods (Moscow, Standartinform) 44 p
[6] Technical Regulations of the Customs Union (TP TC 018/2011) “On the reliability of the wheeled vehicles” 2011
[7] Rotenberg R V 1972 Suspension of the car. Fluctuations and smooth running (Moscow, Mashinostroenie Publ.) 392 p
[8] Khachaturov A A, Afanasiev L V, Vasilyev V S et al. 1976 Dynamics of the "road-tire-car-driver" system (Moscow, Mashinostroenie Publ.) 535 p
[9] Yatsenko N N, Prutchikov O K 1969 Smoothness of the course of trucks (Moscow, Mashinostroenie Publ.) 219 p
[10] Ryabov I M , Chernyshov K V , Gasanov M M , Mukhuchev Sh M 2015 Improving the safety of the car due to the rational choice of tyres, taking into account the characteristics of shock absorbers News of Volgograd State Technical University [Izvestiya Volgogradskogo gosudarstvennogo tehnichestkogo universiteta – in Russian] 10-4(162) 45–49