Theoretical background of experimental methods for studying the influence of technical conditions of shock absorbers on lateral tire reactions

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Abstract. The article studies the technical condition of shock absorbers which influences the occurrence of lateral reactions when the vehicle is passing through a single irregularity under the influence of lateral forces. The lateral reactions determine the properties of the directional and trajectory stability of the car. These properties allow us to consider lateral reactions as diagnostic parameters for the method of operational control of the technical condition of the suspension according to the stability criteria of the car. A mathematical model developed by the authors was applied. The model is based on the dynamics equations of the sprung and non-sprung masses, taking into account the technical condition of the shock absorbers. To describe the longitudinal and lateral reactions, the normalized slip function is used. The process of car movement around a circle was simulated with various parameters of the technical condition of the shock absorbers. Simulation results were processed using approximation and correlation analysis methods. The dependences of changes in the maximum value of lateral reactions on each wheel depending on the technical condition of shock absorbers were obtained. The presence of a strong correlation between the magnitude of the lateral reaction and the technical condition of its own shock absorber is established. Changing the technical condition of improper shock absorbers to a lesser extent affects the lateral reaction, but at the same time reduces the quality of diagnosis. Foundations of the method for conducting a road experiment were developed.

1. Introduction

Course stability and trajectory stability are one of the main properties ensuring safety of vehicles. It is well known that the technical condition of the suspension system has a significant impact on vehicle stability. At the same time, its technical condition is not assessed by stability properties. One of the reasons is the lack of scientific knowledge about the impact of changes in technical conditions of the suspension system on vehicle stability.

There is a road method for monitoring the technical condition of shock absorbers by analyzing kinematic parameters of movement, in particular the angle of vehicle rotation relative to the vertical axis [1]. The method is used for functional diagnostics of the damping system along the vehicle axes. The method cannot be used for the elemental determination of technical conditions due to the impossibility...
of identifying a diagnostic parameter characterizing each shock absorber. The differential diagnosis deals with lateral reactions that occur when the vehicle moves along the curved path. They are force parameters of interaction of an elastic tire with a road surface. Values of lateral reactions depend on many factors: a normal load on the wheel, a lateral adhesion coefficient, an angle of withdrawal, and a wheel rolling mode. The nature of lateral reactions is well known for stationary modes of suspension [2], when shock absorbers do not work, and lateral reactions depend on characteristics of the elastic suspension elements rather than on technical conditions of the dampers. Thus, in order to assess the influence of technical conditions of the suspension system on stability properties, it is necessary to study the vehicle movement under unsteady suspension operation. The study can be analytical and experimental. Road experiments are costly and require planning and preparation. The study was carried out using mathematical simulation methods. The result is a theoretical justification of the road experiment.

2. Materials and methods
We applied a mathematical model used to describe a M1 vehicle moving along the circle with a radius of 15 meters and passing through a single square roughness with a side of 5 centimeters. This configuration forms scheme 1 of the road experiment simulation (Fig. 1, a). The mathematical apparatus includes [3] equations of dynamic equilibrium of the sprung mass for six degrees of freedom; equations of dynamic equilibrium of unsprung masses for one degree of freedom; calculation of longitudinal and lateral reactions using the normalized slip function [4] and taking into account a smoothing ability of the tire and an unsteady suspension operation mode [5]. The road surface was a surface with a zero vertical coordinate, except for the location of a single irregularity, where the coordinate was determined by the disturbance height.

![Figure 1](image-url) Figure 1. Road experiment schemes: a – a single irregularity is located in one section of the road (scheme 1); b - two single irregularities are located along the sides of a vehicle (scheme 2); 1, 5 - single irregularities; 2 - tested vehicle; 3 - the middle line of a path of the inner wheels; 4 - the middle line of a path of the external wheels.

The program code implemented in the SciLab computer environment provides for calculations using the Euler method of numerical integration with a step of 0.001 seconds. There is a satisfactory convergence with results of other road experiments [6], which allows the use of their mathematical apparatus.

The program allows the calculation of vehicle movement parameters with an independent disturbance of the suspension of internal and external wheels. The model contains coordinates of single irregularities displaced along the tracks. Such a configuration of parameters determines scheme 2 of the road experiment simulation (Fig. 1, b).

The efforts of shock absorbers, which are part of the dynamic equilibrium equations, are empirical dependencies on the speed of rod movement. When changing the technical condition, the force is calculated as a product of the function of a working shock absorber by a correction factor \( A \), which characterizes a decrease in damping properties, and varies from 0 to 1.0 corresponds to a shock absorber which has no damping properties; 1 does not change the force function. The values of coefficient \( A \) were
0.1, 0.2, 0.3, 0.55, 0.8, 1.0 for the front shock absorbers; and 0.1, 0.25, 0.4, 0.6, 0.8, 1.0 for the rear ones. The values were set in four cycles, which allowed us to perform calculations for 1296 combinations of conditions of the shock absorber.

3. Results
The dependence of lateral reactions on time was obtained for various values of coefficient \( A \). Figure 2 shows the time dependence of lateral reaction \( R_y \) of the front inner wheel according to scheme 1, when the vehicle is travelling at 10 m/s. The free run starts one second before the wheel passes through the irregularity. The dependences of changes in lateral reactions of the front external and rear wheels, as well as the simulation results according to scheme 2 are similar and not presented graphically. In Figure 2, the solid line denotes lateral reactions for the sound shock absorbers, the dotted line denotes lateral reactions for the defective ones.

![Figure 2](image_url)

**Figure 2.** Characteristics of lateral reaction \( R_y \) of the front inner wheel: a - areas of local diagnoses \((S_1\text{--}S_7)\); b – boundaries of the diagnostic parameter \( R_y(S_1) \).

The simulation shows that a decrease in damping properties of shock absorbers changes temporal characteristics of lateral reactions. The changes form areas \( S_1\text{--}S_4 \) when the front wheels pass through the irregularities and areas \( S_5\text{--}S_7 \) - when the rear wheels pass through the irregularities.

The simulation results were processed. For \( S_1 \) dependences (Fig. 2, b) that describe the boundaries of changes in the maximum value of lateral reaction \( R_y(S_1) \) depending on coefficient \( A \) were obtained. The upper \( R_y(S_1) \) and lower \( R_y(S_1) \) boundary levels were approximated by a rational second-order function:

\[
R_{yij}(S_1)_{h,l} = a(k) \cdot A^2 + b(k) \cdot A + c(k),
\]

where \( a(k), b(k) \) are coefficients determining the degree of dependence \( R_y(S_1)_{h,l} \) on \( A \); \( c(k) \) is the function value at \( A=0 \); \( k \) is the index corresponding to the road experiment design number; \( i, j \) is the wheel index \((i=1 \text{ is the front axle, } i=2 \text{ is the rear axle, } j=1 \text{ – right, } j=2 – \text{ left})\). The numerical values of the parameters and determination coefficients \( R^2(k) \) are presented in Table 1.

| Table 1: Function Parameters \( R_{yij}(S_1)_{h,l} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( R_{y11}(S_1)_{h,l} \) | 462 | -2084 | 5157 | 0.999 | 609 | -2456 | 5469 | 0.999 |
| \( R_{y11}(S_1)_{l} \) | 377 | -2014 | 5055 | 0.999 | 741 | -2614 | 5376 | 0.999 |
| \( R_{y12}(S_1)_{h} \) | 215 | -1697 | 4947 | 0.999 | 419 | -2130 | 6140 | 0.999 |
A correlation analysis was performed for maximum values of lateral reactions $R_{ij}(S_l)$ and absorber damping reduction coefficients $A_i(k)$ (Table 2).

| $R_{ij}(S_l)$ | $A_{j1}(I)$ | $A_{j2}(I)$ | $A_{j1}(2)$ | $A_{j2}(2)$ | $A_{j1}(2)$ | $A_{j2}(2)$ |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $R_{y1}(S_l)$ | -0.997      | -0.004      | 0.005       | -0.994      | 0.001       | 0.004       | 0.065       |
| $R_{y2}(S_l)$ | 0.147       | -0.986      | 0.048       | -0.019      | 0.019       | -0.997      | 0.045       | 0.013       |
| $R_{21}(S_l)$ | -0.09       | -0.998      | -0.86       | 0.363       | 0.009       | -0.126      | -0.882      | 0.043       |
| $R_{22}(S_l)$ | -0.03       | -0.09       | 0.019       | -0.958      | -0.04       | -0.042      | -0.035      | -0.928      |

The results can be used for further studies.

4. Discussion and conclusion

Previous studies [7] show that lateral reactions $R_y$ in $S_1–S_3$ (Fig. 2, a) can be used as diagnostic parameters. These areas are characterized by the greatest level of sensitivity of the parameter to changes in shock absorbers. The nature of the process is unique. Given the similarity of reaction properties, further studies were carried out in $S_i$. Moreover, the maximum value of lateral reaction $R_{yij}(S_l)$ was used as a diagnostic parameter.

The correlation analysis (Table 2) shows that the maximum value of a lateral reaction depends on the technical condition of a wheel’s shock absorber. The effect of shock absorbers of other wheels on the lateral reaction is insignificant. However, they change the lateral reaction even under the constant technical condition of own shock absorbers. This circumstance does not allow for the unambiguous identification of technical conditions of shock absorbers by the value of the lateral reaction. The higher the ambiguity of a diagnosis, the greater the value of the lateral reaction due to the influence of other shock absorbers on technical conditions. Figure 2 shows the line with square markers which indicate the upper boundary of diagnostic parameter $R_y(S_l)$, and the line with circle markers which indicates the lower border. According to [1], the front shock absorbers are serviceable with a damping force of at least 30 % ($A_0=0.3$) of the nominal level. For rear shock absorbers, this indicator is 40 % ($A_0=0.4$). The front inner wheel (Fig. 2, b) with $A_0=0.3$ has a zone of uncertainty of diagnosis $III$ between $L_1=4478$ N and $L_1=4575$ N. If the maximum lateral reaction falls within this range, the own shock absorber can be in both good and bad conditions. If the reaction is in zone $I$, at $R_y(S_l)>L_H$, the absorber is defective; in zone $II$ at $R_y(S_l)<L_L$, it is not defective.

Let us determine the range of coefficient $A$ determined the influence of technical conditions of other shock absorbers on the diagnostic parameter. This assessment can be graphical and analytical. Using the graphical method, it is necessary to build a perpendicular to the abscissa axis from the intersection points (boundary lines $R_y(S_l)_{II}$ and $R_y(S_l)_{I}$ and lines $L_L$ and $L_H$ (Fig. 2, b). The range of coefficient $A$ is determined by values $A_1=0.25$ and $A_2=0.35$. The analytical method is used to solve quadratic equation (1) with $R_y(S_l)=L_L$ and $R_y(S_l)=L_H$. The roots of the equations and calculation parameters for the first and second experimental simulation schemes are presented in Table 3.
Table 3. Parameters and roots of quadratic equations

| $R_{yij}(S_1)$ | $A_0$ | $L_{d(1)}, H$ | $L_{d(1)}, H$ | $A_1(1)$ | $A_2(1)$ | $L_{d(2)}, H$ | $L_{d(2)}, H$ | $A_1(2)$ | $A_2(2)$ |
|----------------|-------|----------------|----------------|-----------|-----------|----------------|----------------|-----------|-----------|
| $R_{i1}(S_1)$  | 0.3   | 4577           | 4478           | 0.25      | 0.35      | 4796           | 4670           | 0.24      | 0.36      |
| $R_{i2}(S_1)$  | 0.3   | 4460           | 4150           | 0.09      | 0.5       | 5540           | 5394           | 0.22      | 0.38      |
| $R_{12}(S_1)$  | 0.4   | 4063           | 3464           | 0.1       | 19.47     | 4370           | 4040           | 0.27      | 0.62      |
| $R_{22}(S_1)$  | 0.4   | 5083           | 3553           | -         | 17.19     | 4836           | 4630           | 0.32      | 0.51      |

An analysis of the range of coefficient $A$ as a difference between $A_2(k)$ and $A_1(k)$, allowed us to compare the diagnostics modes. The larger the range, the higher the probability of first and second order errors. Simulation according to scheme 1 indicates the impossibility of diagnosing the rear external wheel. In this case, the root of quadratic equation $A_1(1)$ is a complex number, the second root is $A_2(1)=17.19$ (Table 3), which falls outside the range of acceptable values of coefficient $A$. Thus, the zone of diagnosis uncertainty covers the range of the coefficient of decreasing damping properties of the shock absorber (Fig. 3, a).

![Figure 3](image-url)

**Figure 3.** The ranges for coefficient $A$: a - according to scheme 1; b - according to scheme 2.

Diagnostic parameter $R_{22}(S_1)$ of the rear inner wheel is of little use. The boundaries of the uncertainty zone are from 0.1 to 1.0. Unambiguously, it is possible to identify the condition of only those shock absorbers whose damping force does not exceed 10% of the nominal value.

The shock absorbers of the front wheels have lower uncertainty, for the external wheel, the range of coefficient $A$ is 0.41; for the inner one, it is 0.1.

According to scheme 2, the simulation of movement is characterized by a smaller variation of the diagnostic parameter (Fig. 3, b). Uncertainty zones are reduced. For the rear internal and external shock absorbers, they are 0.35 and 0.18, respectively. Diagnosis uncertainty for the front external shock absorber is 0.16. A slight increase in uncertainty for the front internal shock absorber is due to the simulation of movement at a constant speed (without rolling).

According to scheme 2, smaller values of the uncertainty diagnosis zone make it more preferable to use as a basis for developing a power method for diagnosing the suspension by the value of lateral reactions when the vehicle moves along a curved path passing through single irregularities.

Uncertainty can be removed by including additional operations of in-depth studies of shock absorbers, for example, using specialized stands [8]. In this case, shock absorbers will be divided into three groups. The first group will include shock absorbers with diagnostic parameter $R_{yij}(S_1)$ which is less than $L_d$. These shock absorbers are workable. The second group includes shock absorbers whose diagnostic parameter $R_{yij}(S_1)$ falls into the uncertainty zone in the range from $L_d$ to $L_H$. For such shock
absorbers, additional diagnostics is required. The third group includes defective shock absorbers with a diagnostic parameter whose value is higher than $L_a$.

Another approach is to determine the maximum permissible value of the diagnostic parameter which will be lower than $L_a$. Shock absorbers of the second group are decommissioned without additional diagnostics. The effectiveness of the approaches is evaluated using the economic and probabilistic method for determining standards of technical operation of vehicles [9].

Despite the purely theoretical nature of the results, they allow us to formulate the basics of the method for conducting a road experiment. At the initial stage, scheme 2 can be simplified as an exception from experiment 5 with a single irregularity (Fig. 1, b), and the car travels clockwise and counterclockwise. In this case, the internal wheels will interact with a single irregularity. By shifting the trajectory to the center of rotation, the external wheels are tested clockwise (right ones) and counterclockwise (left ones). The data obtained at the initial stage make it possible to verify the theoretical results and serve as the basis for planning and conducting road experiments according to scheme 2.

Taking into account that $S_r$~$S_d$ are formed for less than 0.1 second, and the vehicle speed does not exceed 10 m/s, the lateral reaction should be measured on a road section of no longer than one meter. To fix the parameters, it is advisable to use road measuring plates equipped with strain gauges for measuring lateral reactions [10]. By changing the distance from a single irregularity to the slab, it is possible to determine the lateral reaction for any area of local diagnoses.

The theoretical studies allow us to draw the following conclusions. There is a strong correlation of the lateral reaction and the technical condition of the own shock absorber under unsteady suspension operation. The technical condition of other shock absorbers affects the lateral reaction to a much lesser extent. However, the presence of this effect makes it difficult to use a lateral reaction as a diagnostic parameter due to the diagnosis uncertainty. The uncertainty value depends on the scheme of single irregularities which should be taken into account when conducting road experiments.

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