Analysis of Various Types of Elastic Wheel Radii and Establishing Necessity and Sufficiency of Their Application for Various Problems

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Abstract. The wheel has the following radii types: free R_0, static R_{st}, dynamic R_d, rolling r_k. The difference between them can reach 20% depending on the value of tire radial deformation. It is established that at tire operation deformations the rolling radius decreases by no more than 2%. It is known that a wheel radius has a complex, ambiguous influence on car active safety properties: dynamical stability, manageability, brake dynamics. The purpose of this paper is defining the types of wheel radii necessary for the application at the solution of various problems connected to the car active safety properties. The authors conducted the design analysis of the influence of the type of the used radius at the estimation of longitudinal sliding s_x on the form of the obtained $\varphi - s_x$-diagrams. The problem of obtaining s_x is encountered at the mathematical simulation of the properties of active safety of wheeled vehicles as well as at their physical simulation on simulator stands and at the manufacture of automatic unmanned vehicles. It is established that at the calculations of $\varphi - s_x$-diagrams one can apply the close value of free radius instead of a rolling radius value. A more complex problem is providing a rationale of the applied wheel radius in the problems of determining linear deviations, brake way, and car angular orientation. It is connected to complicated and unambiguous interconnections of a wheel radius with the car trajectory parameters. It is determined that at the calculation of car motion trajectory parameters (linear deviations, brake way, angular orientation) one should use the rolling radius value. By the rolling radius value, one should estimate the wheel longitudinal sliding as well as a coupling moment.

Keywords: Tire · Types of radii · Free radius · Static radius · Dynamic radius · Rolling radius · Analysis of application

1 Introduction

A car wheel, equipped with elastic tire and space-stabilized in a specific way, has a significant influence on such car properties as dynamical stability, manageability, brake dynamics. That is why at simulating these properties one should simulate an elastic wheel as well: its geometrical dimensions, elastic and bonding properties, its deformations.

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The wheel has the following radii types: free R_0, static R_{st}, dynamic R_d, rolling r_k. The difference between them can reach 20% depending on the value of tire radial deformation [1–30].

Wheel free radius—half of the wheel external diameter [11].

External wheel diameter—diameter of the largest circumferential section of the wheel raceway at the absence of wheel contact with the bearing surface [11].

Static wheel radius—distance from the wheel center, loaded with only static normal load, to the bearing surface.

Dynamic radius—distance from the wheel center to the bearing surface at wheel motion.

Wheel rolling radius—ratio of the longitudinal component of the wheel advance rate to its angular velocity [11] at the rolling without slide. The rolling radius, defined with the account of possible wheel slide, is also referred to as the kinematic radius [17–20].

Radii types are shown in Fig. 1.

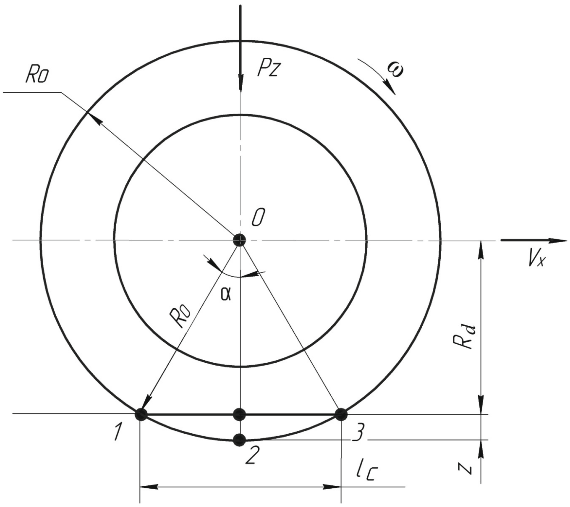

Fig. 1 Wheel diagram

The following designations are taken in Fig. 1: R_0—tire free radius; R_d—tire dynamic radius; P_z—normal wheel load; l_c—contact area length; Z—tire radial camber; $\boldsymbol{\omega}$—wheel angular velocity; α—angle.

Essentially, the rolling radius is an average radius of a wheel rolling without slide. It can be obtained by the approximated dependence (ratio) [2]:

$$r_k \approx R_0 \left[\left(1 - \frac{\arcsin\left(\sqrt{n(2-n)}\right)}{\pi} \right) + \frac{\sqrt{n(2-n)}}{\pi} \right] \tag{1}$$

where n—relative radial tire deformation ($n = \frac{Z}{R_0}$).

In this expression, at $n = 0$ (no radial tire deformation) $r_k = R_0$. At $n = const$ $r_k = const$.

V. A. Petrushov also obtained a corrective dependence of the rolling radius on the tangential elasticity of a diagonal tire and the delivered torque [15]:

$$r_k = r_{k0} - C_{t\beta} \cdot M_k$$

where $C_{t\beta}$—coefficient of the tire torsional stiffness; M_k—torque delivered to a wheel; r_{k0}—rolling radius in the free mode.

Due to a significantly lower tangential elasticity of a radial tire, one can ignore the ratio $r_k = f(M_k)$.

The elastic wheel (tire) radii can have various values. At this one can always observe

$$R_{st} < R_0; \quad R_d \leq R_0.$$

Depending on the tire radial deformation, $R_d <> R_{st} \ \wedge \ R_d = R_{st}$.

The rolling radius $r_k \leq R_0$; $r_k > R_{st}$; $r_k \geq R_d$.

The rolling radius can be also obtained experimentally, using the distance passed by a real wheel for ten rotations, as it is traditionally done in the scientific school of A.I. Fedotov [25]. The experimental results show that with the growth of tire radial deformation the rolling radius decreases to 3% [25]. However, the problems of project forecasting of car active safety properties do not provide a possibility for the experimental determination of a rolling radius; that is why in these cases it is permitted to calculate it by the suggested theoretical dependence (1).

Despite a large number of the research on the rolling motion theory of the elastic tire, the specialists have not reached common grounds in terms of what kind of radius should be applied in this or that problem. However, the difference between R_d and r_k, for example, can reach up to 20%, and this naturally leads to the difference in the calculations using these radii.

2 Purpose of Research

The purpose of this paper is defining the types of wheel radii necessary for the application at the solution of various problems connected to the car active safety properties.

3 Research Method

At the calculation of input parameters, it is required to learn the length of the tire contact area with a road. This length is defined simultaneously by a free radius (a larger wheel has a longer contact area) and a dynamic radius connected to a current radial tire deformation.

A disturbing moment at the driven wheel due to the lateral reaction of the bearing surface depends on two factors determining the reaction arm: the longitudinal tilt of the wheel rotation axis and the longitudinal displacement of the section with static friction by means of which the lateral reaction is implemented and to the center of which it is applied. That is why, to calculate the specified moment (torque), it is required to obtain a free radius and the radii for the calculation of a contact area length.

A more complex problem is providing a rationale for the selection of the applied wheel radius in the problems of defining $\varphi - s_x$-diagrams. To build such diagram, it is necessary to get the coefficient of longitudinal wheel sliding s_x. The problem of obtaining the coefficient of longitudinal wheel sliding (CLWS) s_x is encountered at the mathematical simulation of the properties of active safety of wheeled vehicles as well as at their physical simulation on simulator stands and at the manufacture of automatic unmanned vehicles.

The authors also conducted the design analysis of the influence of the used radius type at the calculation of CLWS on the form of the obtained $\varphi - s_x$-diagrams [2], the results of which are given in Figs. 2 and 3. To calculate $\varphi - s_x$-diagrams, the authors used the measuring and control method (i.e., applying the coefficient of proportionality of static friction) [2].

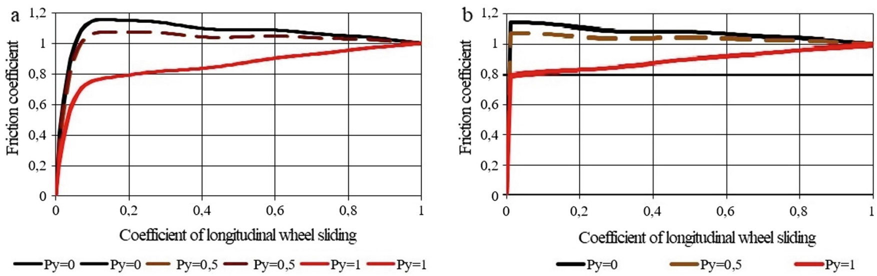

Fig. 2 Design $\varphi - s_x$-diagrams at various values of lateral force occurring before the braking start and obtained at the calculation of the value s_x: **a**—on the free radius and rolling radius; **b**—on the dynamic radius

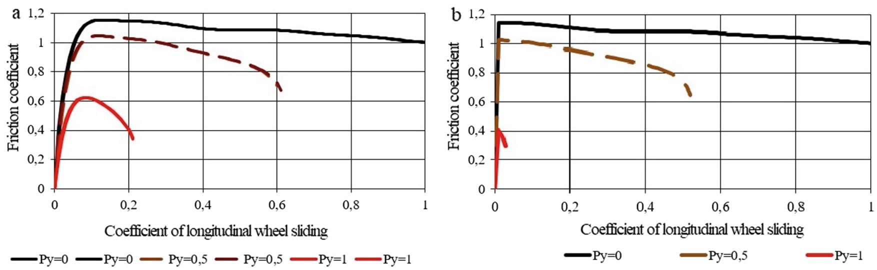

Fig. 3 Design $\varphi - s_x$-diagrams at various values of lateral force occurring before the braking start and obtained at the calculation of s_x: **a**—on the free radius and rolling radius; **b**—on the dynamic radius

On the basis of the conducted analysis, the authors drew a conclusion on the reasonability at the calculation of CLWS s_x of the tire rolling radius (but not a dynamic one!). At the calculations of $\varphi - s_x$-diagrams, one can apply the close value of free radius instead of the rolling radius value. Apparently, in terms of mechanics, it would be better to use the rolling radius value. But as it is different from the free radius even at maximum permitted tire deformation by no more than 2%, and such difference does not significantly influence the design $\varphi - s_x$-diagrams at various values of lateral force, occurring before or after the start of wheel braking, it is not necessary to complicate the problem with the calculation of the rolling radius in each motion moment because this increases the time of calculation while the use of free radius provides the same result. To approximately calculate the rolling radius with a sufficient precision of practical calculations, it is possible to use the ratio (dependence) provided above (1).

A more complex problem is providing a rationale of the applied wheel radius in the problems of determining linear deviations, brake way, and car angular orientation. It is connected to complicated and unambiguous interconnections of the wheel radius with the car trajectory parameters.

Figures 4 and 5 show the parameters of the car M1 trajectory, calculated by the software package Stabauto, at the application of rolling and dynamic radii for such calculations.

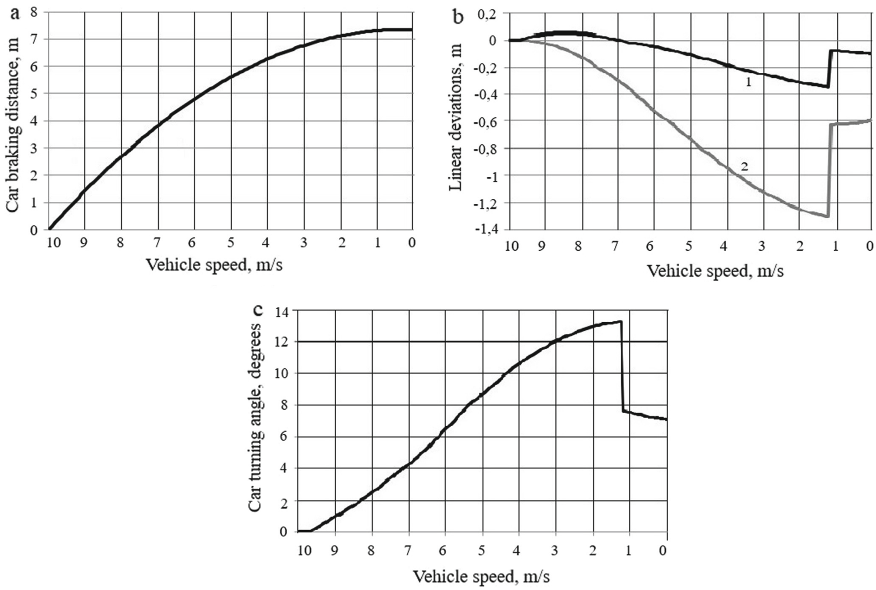

Fig. 4 Design parameters of the car motion trajectory at the use of a wheel dynamic radius (braking mode at the right rotation of the radius 35 m on dry asphalt concrete without ABS with the initial velocity 10 m/sec): **a** brake way; **b** linear axial deviations; **c** angular orientation; 1—deviations of the back axis; 2—deviations of the front axis

Figures 4 and 5 show that the application of the dynamic radius instead of the rolling one for the calculation of the car trajectory parameters do not influence the values of linear deviations, brake way, and the car angular orientation but results in unstable solution, which does not provide for the objective assessment of active safety parameters of the car at mathematical simulation.

On wet asphalt concrete as well as on any cover at the presence of ABS, the physical phenomenon of the influence of radii types on the characteristics of the simulated car motion trajectory is preserved; however, this influence is not so explicit.

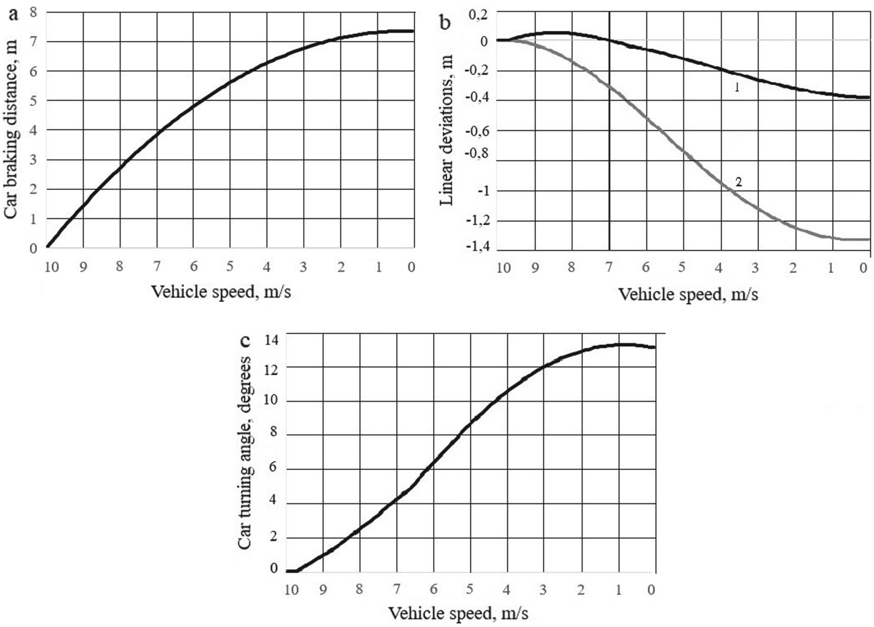

Fig. 5 Design parameters of the car motion trajectory at the use of a wheel rolling radius (braking mode at the right rotation of the radius 35 m on dry asphalt concrete without ABS with the initial velocity10 m/sec): **a** brake way; б—linear axial deviations; **b** angular orientation; 1—deviations of the back axis; 2—deviations of the front axis

4 Conclusion

1. There are five types of the elastic wheel radius and the difference in their values reaches 20%.
2. It is established that the wheel radius has a complex, ambiguous influence on the car active safety properties: dynamical stability, manageability, brake dynamics.
3. The authors analyzed the influence of the applied types of car wheel radii on the results of mathematical simulation of the car active safety properties.
4. At the calculation of wheel longitudinal sliding s_x, one should apply the rolling radius (but not the dynamic one!). At the calculations of $\varphi - s_x$-diagrams, one can apply the close value of free radius instead of the rolling radius value.
5. At the calculation of car motion trajectory parameters (linear deviations, brake way, angular orientation), one should use the rolling radius. By the rolling radius value, one should estimate the wheel longitudinal slide as well as a coupling moment.

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