

Regarding the issue of determining the deceleration of a two-axle vehicle with a damaged brake system

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Abstract. Problem. During the study of the circumstances of the occurrence of road accidents, the experts of the automotive technical expertise face a problem of choosing the mathematical model for determining the deceleration of a two-axle vehicle with a faulty working brake system. The search for a universal method for calculating the amount of deceleration of a two-axle vehicle with a faulty working brake system is an urgent scientific task that will expand the understanding of the physical processes on which the provisions of the theory of the car are based. **Goal.** The aim of the work is to generalize theoretical research to determine the deceleration of a two-axle vehicle with a faulty working brake system. **Methodology.** The approaches adopted in the work to solve this goal are based on the analysis of methods for determining the deceleration of two-axle wheeled vehicles. **Results.** The obtained calculated values of deceleration of a two-axle wheeled vehicle with different external factors allowed to establish the features of the use of different methods in the practice of automotive technical expertise. It is established that taking into account the angle of the road surface towards the roadside and taking into account the coefficient of resistance of car tires can change the extent of deceleration of a two-axle wheeled vehicle with a faulty service brake system. **Originality.** The proposed universal method for determining the deceleration of a two-axle wheeled vehicle with a faulty working brake system, allows to take into account the influence of rolling resistance of tires and the angle of inclination of the road surface towards the roadside when studying the circumstances of a traffic accident. **Practical value.** The results obtained can be recommended in the practice of automotive technical expertise or in research related to determining the braking performance of two-axle wheeled vehicles.

Key words: braking efficiency, braking rate, vehicle deceleration, brake system malfunction, braking process modeling.

Introduction

During the reconstruction of the circumstances of a traffic accident (accident), experts in automotive technical examination often establish the facts of braking a wheeled vehicle (WV) with loss of efficiency, indicating the failure of individual contours of the brake drive or brake mechanisms of the service brake system.

This raises the question of choosing a method for determining the braking performance of WV, which has damage to the service brake system. It should be noted that the proposed method should be convenient and universal and should be based on known parameters that can be unambiguously determined during the reconstruction of the circumstances of the accident or from reference or scientific and technical literature.

Analysis of publications

It is known [1–13] that during the study of the braking efficiency of a wheeled vehicle, the main parameters that characterize the process of its braking are: the braking distance and the achieved amount of deceleration of the vehicle. In the scientific and technical literature [4,14–16], depending on the order of locking vehicle wheels, a equation is proposed on the basis of which it is possible to determine the deceleration of a two-axle vehicle.

Similar equations, as shown by the analysis of [17], are proposed to be used in expert practice for two-axle WV, but the list of types of a damaged of the service brake system of such vehicles is limited.

Purpose and Tasks

The purpose of this work is to generalize theoretical research to determine the deceleration of a two-axle vehicle with a damaged service brake system.

To achieve this goal, it is necessary to perform an analysis of equations to determine the deceleration of a two-axle vehicle with a damaged service brake system and propose a universal equation that would take into account the external conditions of the vehicle.

Methods for determining the deceleration of a two-axle vehicle with a damaged service brake system

UN International Standard №13 stipulates that the vehicle deceleration (j) can be calculated from the equation (1) used to assess the braking performance of certified vehicles.

$$j = zg, \quad (1)$$

where z - the braking rate of the wheeled vehicle; g - the free-fall acceleration due to gravity, m/s^2 .

However, it is known that, during the operation of the vehicle, in its service brake system may occur malfunctions of the brake mechanisms of one or more wheels or the damaged of the drive contours. In such cases, for two-axle vehicles, when conducting research on the circumstances of the accident, experts determine the deceleration of equation (1) by taking into account the types of malfunction (Table 1) [17] of the vehicle service brake system. In the case of increasing the number of axles or in the event of other malfunctions that lead to a decrease in the braking efficiency of the vehicle, in expert practice, unjustified complication of the procedures of automotive technical examination using similar vehicles.

Analysis of the equations shown in table 1 showed that they do not take into account the effect of rolling resistance are not braking wheels but located in contact with the road surface, and do not take into account the slope of the road towards the roadside. The analysis of scientific and technical works [4,14–16] showed that the dependences given in Table 1 can be replaced by the equation (2), which gives a 100% coincidence of the calculation results.

$$z = \frac{b_g f_{x1} + a_g f_{x2}}{L - h_g (f_{x1} - f_{x2})}, \quad (2)$$

where a_g and b_g - the corresponding coordinates of the location of the center of gravity of the vehicle relative to its front and rear axles, m; h_g - the height of the center of gravity of the vehicle relative to the road surface, m; f_{x1} and f_{x2} - the corresponding utilized adhesion between the tires of vehicle wheels on the axle and the road surface; $L = a_g + b_g$ - wheelbase of the vehicle, m.

Table 1. Equations for determining the braking rate of a two-axle vehicle with a service brake system having a corresponding damage

Number	Type of malfunction of the vehicle service brake system	Equations to determine the braking rate
1	Does not brake one front wheel	$\frac{(L + a_g) f_x^{\max}}{2L + h_g f_x^{\max}}$
2	Does not brake one rear wheel	$\frac{(L + b_g) f_x^{\max}}{2L - h_g f_x^{\max}}$
3	Only one front wheel brakes	$\frac{b_g f_x^{\max}}{2L - h_g f_x^{\max}}$
4	Only one rear wheel brakes	$\frac{a_g f_x^{\max}}{2L + h_g f_x^{\max}}$
5	Only the front wheels brake	$\frac{b_g f_x^{\max}}{L - h_g f_x^{\max}}$
6	Only the rear wheels brake	$\frac{a_g f_x^{\max}}{L + h_g f_x^{\max}}$
7	Only the left (right) side of the vehicle brakes	$\frac{f_x^{\max}}{2}$

The analysis of scientific and technical literature [18] showed that similar dependences can be obtained for the traction regime, but in this paper such equations will not be considered.

The utilized adhesion are not difficult to determine from equation (3), which takes into account the influence of the coefficient of rolling resistance of the vehicle wheels (f_0) and the slip (S) of the tire relative to the road surface, which varies in the range from 0 to 1.

$$f_{xi} = \frac{a_i S}{S^2 + b_i S + S_c^2} + f_0, \quad (3)$$

where a_i and b_i - coefficients that determine the shape of the utilized adhesion curve, which varies depending on the slip (S) of the tire of the

car wheel in the range from 0 to 1; S_c – the critical slip value (S) at which the maximum of the utilized adhesion (f_x^{\max}) of the tire of the vehicle wheel relative to the road surface is reached.

If we assume that $S = S_c$ then equation (3) becomes static, and the results of the calculation provided it is used in equation (2), can be compared with the results of the calculation by equations given in table 1, provided that $f_0 = 0$.

The results of calculations by the corresponding equations shown in table 1, and based on the use of equation (2), for example, for the data shown in table 2, for ease of analysis are given in table 3.

Table 2. Initial data for calculation

Parameter	Designation	Value
Rolling resistance coefficient	f_0	0.02
Maximum utilized adhesion of the tire wheel of the vehicle	f_x^{\max}	0.8
The utilized adhesion of the tire of the vehicle wheel locked	f_{xb}	0.6
The longitudinal coordinate of the location of the center of gravity of the vehicle relative to its front axis, m	a_g	2.78
The longitudinal coordinate of the location of the center of gravity of the vehicle relative to its rear axis, m	b_g	1.42
The height of the center of gravity of the vehicle relative to the road surface, m	h_g	0.9
The critical value of slip (S) at which the maximum utilized adhesion is reached	S_c	0.2
The angle of slope of the road surface towards the roadside, deg	β	3

The coefficients a_i and b_i , which determine the shape of the utilized adhesion curve (f_{xi}) according to the equation (3), can be determined from the equation (4) and (5), respectively.

$$a_i = \frac{(f_x^{\max} - f_0)(f_{xb} - f_0)(1 - S_c)^2}{f_x^{\max} - f_{xb}}, \quad (4)$$

$$b_i = \frac{(f_{xb} - f_0)(1 + S_c^2) - 2(f_x^{\max} - f_0)S_c}{f_x^{\max} - f_{xb}}, \quad (5)$$

where f_{xb} – the utilized adhesion of the tire of the vehicle wheel locked.

Table 3. The results of calculations j based on equation (1), equations in table 1, and equation (2)

Number	Type of malfunction of the vehicle service brake system	The results of calculations j based on		
		equation (1) and equations in table 1	equation (1) and (2) excluding f_0	equation (1) and (2) including f_0
1	Does not brake one front wheel	6.004	6.004	6.053
2	Does not brake one rear wheel	5.739	5.739	5.798
3	Only one front wheel brakes	1.452	1.452	1.628
4	Only one rear wheel brakes	2.394	2.394	2.521
5	Only the front wheels brakes	3.198	3.198	3.345
6	Only the rear wheels brakes	4.434	4.434	4.503
7	Only the left (right) side of the vehicle brakes	3.924	3.924	4.022

In the case of braking only one wheel of the vehicle axle, the equation (3) must be modified into the equation (6) when using it in the equation (2), provided that under the left and right wheel utilized adhesion are the same.

$$f_{xi} = \frac{0.5a_i S}{S^2 + b_i S + S_c^2} + f_0, \quad (6)$$

In the case when under the left and right wheels of the vehicle the utilized adhesion have different values of equation (3) it is necessary to use together with equation (7), which allows calculating the average value of the utilized adhesion axle [3].

$$f_{xi} = \frac{f_{xi}^{left} + f_{xi}^{right}}{2}, \quad (7)$$

In equation (7) designated: f_{xi}^{left} and f_{xi}^{right} – the corresponding utilized adhesion of the tires of the left and right wheels of one axle; the su-

perscripts "left" and "right" indicate that the parameter refers to the left or right side of the vehicle.

The utilized adhesion (f_{xi}^{left} and f_{xi}^{right}) of the left and right wheels of one axle of the vehicle can be determined using equation (3), separately calculating the coefficients a_i and b_i for the left and right wheels, even if the maximum of the utilized adhesion (f_x^{max}) have different values.

By the way, equation (7) can also be used together with equation (3) instead of equation (6) if it is necessary to determine the utilized adhesion of the axle in the case when one or both of the wheels of the axle are not braking. In such a case, the wheel that does not brake will have the value $S = 0$ [8,19].

It can be seen from Table 3 that taking into account the coefficient of rolling resistance of a car tire relative to the surface of the road surface slightly increases the value of the braking rate (z), and therefore increases the value of the deceleration of the wheeled vehicle.

If we consider the movement of a two-axle vehicle on the surface of the road surface, which has a small slope towards the side of the road, intended for the removal of liquid precipitation, then equation (2) is transformed into equation (8) according to the preliminary studies performed in the work [20].

$$z = \frac{C_1 D^{left} + C_2 D^{right}}{2BL - h_g (C_1 A^{left} + C_2 A^{right})}, \quad (8)$$

where A^{left} , A^{right} , C_1 , C_2 , D^{left} and D^{right} – components equation (8) determined by the corresponding equations (9) – (14).

$$A^{left} = f_{x1}^{left} - f_{x2}^{left} \quad (9)$$

$$A^{right} = f_{x1}^{right} - f_{x2}^{right} \quad (10)$$

$$C_2 = B \cos(\beta) - 2h_g \sin(\beta) \quad (11)$$

$$C_1 = 2B - C_2 \quad (12)$$

$$D^{left} = b_g f_{x1}^{left} + a_g f_{x2}^{left} \quad (13)$$

$$D^{right} = b_g f_{x1}^{right} + a_g f_{x2}^{right} \quad (14)$$

where β – the angle of slope of the road surface towards the roadside, deg; B – the average value

between the track of the front and rear axles of the vehicle, m.

It can be seen from equation (8) that the braking of the left and/or right wheels of a wheeled vehicle will have different effects on its braking rate.

Assuming that the average value between the track of the front and rear axles of vehicle is equal to, for example 1.98 m, we will perform calculations according to equation (8).

For ease of analysis, we summarize the calculation results in Table 4.

Table 4. The results of calculations j based on equation (1) and equation (8)

Number	Type of malfunction of the vehicle service brake system	The results of calculations j based on equation (1) and (8)		
		excluding f_0 when $\beta = 0^\circ$	including f_0 when $\beta = 0^\circ$	including f_0 when $\beta = 3^\circ$
1	Does not brake one front wheel (left / right)	6.004 / 6.004	6.053 / 6.053	6.131 / 5.964
2	Does not brake one rear wheel (left / right)	5.739 / 5.739	5.798 / 5.798	5.690 / 5.906
3	Only one front wheel brakes (left / right)	1.452 / 1.452	1.628 / 1.628	1.707 / 1.550
4	Only one rear wheel brakes (left / right)	2.394 / 2.394	2.521 / 2.521	2.619 / 2.413
5	Only the front wheels brakes	3.198	3.345	3.345
6	Only the rear wheels brakes	4.434	4.503	4.503
7	Only the left (right) side of the vehicle brakes or diagonally left front and right rear / right front and left rear	3.924 (3.924) or 3.924 / 3.924	4.022 (4.022) or 4.022 / 4.022	4.208 (3.836) or 3.993 / 4.052

It can be seen from the table that in the absence of a slope of the road surface towards the roadside, the calculations to equation (8) coin-

cide with the calculations given in Table 3.

As the analysis of modeling results (Table 4) showed, the difference in calculations based on different equations (excluding the rolling resistance of the wheels, including the rolling resistance of the wheels, excluding the slope of the road surface towards the roadside and including the slope of the road towards the roadside) can reach 8-9% when the angle of slope of the surface of the road surface towards the roadside is no more than 3 degrees, and including the rolling resistance of the wheels by 11%. With an increase in the angle of slope of the surface of the road surface towards the roadside to 6 degrees, the difference in calculations increases to 18-20%, which can significantly affect the conclusion of the automotive technical expertise.

Compared with the simulation results (Table 3), in the case of using a flat braking model of a two-axle vehicle, the difference in the calculations based on the equations shown in Table 3 can be 5-9%, which can also affect the results of the expert view, therefore neglecting the resistance rolling of vehicle wheels, when determining the braking rate of a two-axle vehicle with a damaged service brake system, is also not advisable.

Neglecting the peculiarity of the structure of the surface of the road surface (the slope towards the roadside (β)) is also inappropriate and must be taken into account when writing the conclusions of the study of the circumstances the emergence of the traffic incident, since, as studies have shown, on average, the calculation error can reach 6-10% at typical road surface slope angles up to 3 degrees. As the angle of slope of the road surface increases, the error increases proportionally.

If we consider similar approaches to determining the deceleration of multi-axle wheeled vehicles or vehicles with trailers, then the proposed equation (8) will take a slightly more complicated mathematical form, as shown in scientific works [1,3,7,8,12,13], but and in this case it is not difficult to including the influence of rolling resistance and the angle of slope of the road surface towards the roadside when determining the deceleration of the vehicle as a result of its braking with a damaged service brake system.

Conclusion

Based on the analysis of scientific and technical literature, it was established that the method of determining the deceleration of a vehicle with a damaged service brake system should including

the peculiarities of the influence of the rolling resistance of vehicle wheels and the angle of slope of the surface of the road surface towards the roadside, since they can affect the results of conclusions by up to 18% the circumstances of the occurrence of road traffic incident in the practice of automobile technical expertise.

A comparison of the results of simulated simulations of a flat braking model of a two-axle vehicle with a spatial model made it possible to establish that the difference in calculations of the amount of deceleration can be from 5 to 9% when the surface of the road surface is slope towards the roadside by no more than 3 degrees, which can affect the results of the expert conclusion, therefore neglecting this fact is inadmissible and must be including when drawing up the conclusions of the investigation into the circumstances of the traffic accident. With an increase in the angle of slope of the road towards the roadside, the percentage of calculation error increases proportionally and can reach 18-20% with an increase slope of the surface of the road surface up to 6 degrees.

The obtained ideas about the regularities of determining the deceleration of the vehicle depending on the coefficient of rolling resistance and the angle of slope of the surface of the road surface towards the roadside allow us to provide recommendations on taking these factors including when writing the expertise conclusions of the circumstances of the occurrence of a traffic accident.

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this scientific paper.

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Щодо питання визначення уповільнення двовісного транспортного засобу з несправною робочою гальмовою системою

Анотація. Проблема. Під час дослідження обставин виникнення дорожньо-транспортних подій перед експертами автомобільної технічної експертизи виникає питання щодо вибору математичної моделі визначення уповільнення двовісного транспортного засобу з несправною робочою гальмовою системою. Пошук універсального методу розрахунку величини уповільнення двовісного транспортного засобу з несправною робочою гальмовою системою є актуальним науковим завданням, яке дозволить розширити розуміння фізичних процесів на яких базуються положення теорії автомобіля. **Мета.** Метою роботи є узагальнення теоретичних досліджень з визначення уповільнення двовісного транспортного засобу з несправною робочою гальмовою системою. **Методологія.** Прийняті в роботі підходи до вирішення поставленої мети базуються на аналізі методів визначення уповільнення двовісних колісних транспортних засобів. **Результати.** Отримані розрахункові величини уповільнення двовісного колісного транспортного засобу при різних зовнішніх факторах дозволили встановити особливості використання різних методів в практиці автомобільної технічної експертизи. Встановлено, що врахування куту нахилу поверхні дорожнього покриття в бік узбіччя та врахування коефіцієнту опору шин автомобільних коліс, може на 18% змінити величину уповільнення двовісного

колісного транспортного засобу з несправною робочою гальмовою системою у разі виконання дослідження з автомобільної технічної експертизи під час визначення обставин виникнення дорожньо-транспортної події. **Оригінальність.** Запропонований універсальний метод визначення уповільнення двовісного колісного транспортного засобу з несправною робочою гальмовою системою, дозволяє врахувати особливості впливу величини опору коченню шин автомобільних коліс та кут нахилу поверхні дорожнього покриття в бік узбіччя під час дослідження обставин виникнення дорожньо-транспортної події. **Практичне значення.** Отримані результати можуть бути рекомендовані в практиці автомобільної технічної експертизи або під час виконання досліджень пов'язаних з визначенням ефективності гальмування двовісних колісних транспортних засобів.

Ключові слова: ефективність гальмування, коефіцієнт гальмування, уповільнення транспортного засобу, несправність гальмової системи, моделювання процесу гальмування.

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