Experimental study of the factors affecting the parameters of emergency braking process for vehicles of category M₁

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Abstract. The paper presents the results of an experimental study of the parameters of emergency braking process for vehicles of category M₁, wherein disclosed is the influence of a combination of factors such as: actual loading of a vehicle, the presence of ABS, EBD, BAS systems, a trailer of up to 750 kg, condition of the road surface, and seasonality types of tires. As a result of the study, the actual values of the steady-state deceleration \( j_{\text{уст}} \) and its rise time \( t_{\text{вр}} \), were obtained, and their comparative analysis with the recommended standard values was carried out. The paper also presents reliable mathematical models in terms of their practical application during the reconstruction of road traffic accidents.

1. Introduction

Road traffic accidents, unfortunately, are an integral part of road transport operation and are among the leading causes of mortality in peacetime. According to the World Health Organization (WHO) [4], road traffic accidents result in the deaths of more than 1.35 million people around the world each year and leave 50 million people with injuries. About 170 thousand road traffic accidents annually occur in the Russian Federation, as a result of which people of employable age and children under 16 die and get injured (figure 1).

![Traffic accident statistics in the Russian Federation for 2008 – 2019.](image)

Figure 1. Traffic accident statistics in the Russian Federation for 2008 – 2019.

Objective and reliable conclusions during the reconstruction of road traffic accidents, render it possible to make justified procedural decisions with respect to questions of guilt of the participants of a road traffic accident, exclude repeated expert examinations and allow making decisions on road safety, including the issues of road traffic organization improvement [8].

Since most road traffic accidents are associated with emergency braking of vehicles, when performing the road-transport examination during the reconstruction of road traffic accidents, one of the important criteria for assessing this process is the values of the steady-state deceleration and its rise time. Based on these values, experts make calculations and assess, from a technical point of view, the...
driver’s behaviour in accordance with the Traffic Regulations and the driver’s ability to avoid the traffic accident [2,14].

The existing road-transport examination techniques do not contain sufficient information on the values of the steady-state deceleration and its rise time for vehicles, equipped with modern active safety systems. During the reconstruction of road traffic accidents, these values are accepted according to the methodological recommendations, developed and approved by the All-Union Research Institute of Judicial Examinations of the Ministry of Justice of the USSR [3,6,7,10,12] more than 40 years ago, as well as to the regulatory guidelines in accordance with TR CU 018/2011 “On safety of wheeled vehicles” [13], wherein the influence of the wheel-to-road cohesion coefficient as well as loading of a vehicle and the ABS system is accounted for, which does not fully correspond to the actual assessment of the actual values of the steady-state deceleration and its rise time. Currently, the design of a vehicle brake control has been significantly improved and, in particular, in addition to the existing systems – Anti-lock Braking System (ABS) and Electronic Brake Distribution (EBD) system – the Brake Assist System (BAS), aimed at minimizing the braking distance and increasing vehicle deceleration, is being actively introduced [11,]. Thus, it is not correct to use in expert practice the recommended and standard values of the steady-state deceleration and its rise time, since the resulting expert conclusions can be unreliable.

In connection therewith, to improve the reliability and objectivity of expert conclusions during the reconstruction of road traffic accidents, clarification of the steady-state deceleration and its rise time, as well as the development of methods for reconstruction of road traffic accidents according to the parameters of braking process for vehicles of category M₁, equipped with ABS, EBD and BAS systems, are required [14].

2. Materials and methods

To conduct experimental studies and determine the actual values of the steady-state deceleration and its rise time for vehicles of category M₁, the selection of the most significant factors was carried out using the method of a priori ranking in accordance with the flow diagram (figure 2) [1].

![Flow diagram for a priori ranking of factors.](image)

Reliability of the influence of the factors is confirmed by the concordance coefficient value $W = 0.71$. The diagram for a priori ranking is presented in figure 3.
Figure 3. Diagram for a priori ranking: \(x_1\) is the wheel-to-road cohesion coefficient, \(x_2\) is vehicle loading, \(x_3\) is the presence of modern brake systems, such as ABS, EBD, BAS, \(x_4\) is the tire seasonality type, \(x_5\) is the presence of a trailer of up to 750 kg, \(x_6\) is year of manufacture of a vehicle, \(x_7\) is the tire pressure, \(x_8\) is the height of the tire tread pattern, \(x_9\) is ambient temperature, \(x_{10}\) is the pedal effort.

From the diagram it follows that according to the experts’ opinion the most significant factors are \(x_1, x_2, x_3, x_4, x_5\), and the remaining factors have no significant impact and therefore are not subjected to further consideration.

To determine the actual values of the steady-state deceleration and its rise time for vehicles of category \(M_1\), taking into account such factors as \(x_1\) – the wheel-to-road cohesion coefficient; \(x_2\) – vehicle loading; \(x_3\) – the presence of ABS, EBD, BAS systems; \(x_4\) – the tire seasonality type; \(x_5\) – the presence of a trailer of up to 750 kg, an experimental study was conducted.

To determine the actual values of the steady-state deceleration \(j_{fsd}\) and its rise time \(t_{fr}\) for vehicles of category \(M_1\), the conditions, limitations and assumptions for conducting the experiment in road conditions were determined according to the interstate standard GOST 33997-2016 “Wheeled vehicles. Safety requirements for operation and methods of inspection” [5] and considering the test instrument maintenance manual. The full-scale experiment was carried out in road conditions of St. Petersburg in the autumn-winter and spring-summer period for vehicles of category \(M_1\), equipped with ABS, EBD, BAS systems with operable brake systems, taking into account the actual vehicle loading, the presence of a trailer of up to 750 kg, condition of the road surface, and the tire seasonality type with operating conditions accounted for (figure 3). The vehicles, during the experiment, had different loading, namely, of 20 to 100%. The trailer was used, both in running order at full efficiency, and with loading of 50%.

The exemplified experimental results and the actual values of the steady-state deceleration and its rise time for vehicles of category \(M_1\) are presented in table 1.

Table 1. The results of the actual values of the steady-state deceleration and its rise time for vehicles of category \(M_1\), equipped with ABS, EBD, BAS systems with vehicle loading of 20% .

| Condition of the road surface | Seasonality type of tires | \(j_{fsd}\) | \(t_{fr}\) | \(j_{fsd}+\) trailer of up to 750 kg | \(t_{fr}+\) trailer of up to 750 kg | \(j_{fsd}\) trailer of up to 750 kg with loading | \(t_{fr}\) trailer of up to 750 kg with loading |
|-----------------------------|----------------------------|-------------|-----------|----------------------------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|
| wet asphalt/\(\phi = 0.45\) | studded                    | 5.79        | 0.27      | 5.32                             | 0.26                          | 5.22                                           | 0.26                                          |
|                             | frictional                 | 6.07        | 0.27      | 5.61                             | 0.26                          | 5.41                                           | 0.26                                          |
|                             | all-season                 | 6.85        | 0.29      | 6.55                             | 0.28                          | 6.27                                           | 0.28                                          |
|                             | summer                     | 8.3         | 0.3       | 7.42                             | 0.3                           | 7.22                                           | 0.3                                           |
|                             | studded                    | 6.02        | 0.31      | 5.63                             | 0.31                          | 5.45                                           | 0.31                                          |
|                             | frictional                 | 6.45        | 0.3       | 5.75                             | 0.3                           | 5.61                                           | 0.3                                           |
|                             | all-season                 | 6.8         | 0.31      | 5.92                             | 0.31                          | 5.22                                           | 0.31                                          |
|                             | summer                     | 8.2         | 0.35      | 6.38                             | 0.33                          | 5.9                                            | 0.32                                          |
| dry asphalt/\(\phi = 0.75\) | studded                    | 6.02        | 0.31      | 5.63                             | 0.31                          | 5.45                                           | 0.31                                          |
|                             | frictional                 | 6.45        | 0.3       | 5.75                             | 0.3                           | 5.61                                           | 0.3                                           |
|                             | all-season                 | 6.8         | 0.31      | 5.92                             | 0.31                          | 5.22                                           | 0.31                                          |
|                             | summer                     | 8.2         | 0.35      | 6.38                             | 0.33                          | 5.9                                            | 0.32                                          |
It was also revealed that the values of the steady-state deceleration $j_{ss}$ and its rise time $t_{tr}$ change due to the regular influence of a combination of factors affecting simultaneously the said values, which is confirmed by multifactorial dependencies.

The dependency diagram for the influence of a combination of factors, including ABS, EBD and BAS systems, the actual vehicle loading, the presence of a trailer of up to 750 kg, condition of the road surface, and the tire seasonality type, with operating conditions accounted for, is presented in figure 4. Based on the results according to the diagrams, a comparative analysis, confirming the difference on average up to 20% between the actual values and the recommended standard values according to requirements by the All-Union Research Institute of Judicial Examinations and TR CU 018/2011, was carried out. Therefore, the expert’s opinion, for example, when calculating the stopping distance or the speed of a vehicle, may vary within the same range.

Thus, the use of actual values of the studied parameters will improve the reliability of expert investigation during the reconstruction of road traffic accidents.

**Figure 4.** Comparative analysis of experimental and recommended standard values.

From the graphical analysis it follows that the values of the steady-state deceleration of a vehicle and its rise time regularly change. The difference in values, in contrast to the standard ones, is on average about 20%. Therefore, the expert’s opinion, for example, when calculating the stopping distance, may vary within the same range, which results to unreliable conclusions with respect to the studied subject matter during the reconstruction of road traffic accidents.

The experimental results and their processing made it possible to obtain reliable mathematical models, predicting the values of the steady-state deceleration and its rise time for vehicles of category M₁, taking into account the aforesaid factors. The resulting mathematical models are presented in table 2.

| Table 2. Mathematical models. |
|-------------------------------|

Regression equations, $y = f(x)$  
$y_{ad} = 3.37048 + 0.885714x_1 + 0.406536x_2 + 0.758857x_3 + 0.1985x_4 + 0.140333x_5 - 0.74975(x_5)^2 - 0.95175x_6(x_5)^2$  
$y_{tr} = 0.156262 + 0.0487381x_1 + 0.02625x_2 + 0.0112619x_3 - 0.00288889x_4 + 0.01125x_4x_5 + 0.0002x_5x_6 - 0.02275(x_5)^2 + 0.00875x_6x_7 - 0.02975x_7(x_5)^2 - 0.0015x_8x_9$  
$y_{id} = 5.60057 + 0.666579x_1 + 0.208489x_2 - 0.320513x_4x_5 + 0.069525x_8x_9 + 0.0536875x_9x_5 + 0.477422(x_2)^2 - 0.112763x_3x_5 + 0.106088x_8x_9 + 0.0601875x_9x_5 - 0.102232(x_2)^2 - 0.195328x_8x_9 + 0.0072657x_3x_5x_9 + 0.225684x_7x_8x_9 - 0.268542(x_2)^2$  
$y_{tr} = 0.274783 + 0.0262522x_5 + 0.0169398x_5 + 0.00388616x_5 - 0.0046875x_4 + 0.0024442x_5 - 0.0106125x_5x_6 - 0.00383125x_5x_7 + 0.001375x_5x_8 + 0.0144844(x_2)^2 + 0.0031125x_5x_9 - 0.001875x_9x_4 - 0.00660937(x_2)^2 + 0.00615937x_9x_5x_9 - 0.007125x_9x_4x_9 + 0.00139688x_9x_5x_9 + 0.00125x_9x_5x_9 - 0.00514687x_9x_5x_9 |

**Table 2.** Mathematical models.

| Determination coefficient, $R^2$ |
|----------------------------------|
| 91.2 % |
| 99.7 % |
| 93.2 % |
| 97.7 % |
The practical significance of mathematical models resides in the possibility of using thereof in determining the steady-state deceleration and its rise time for vehicles of category M₁, when it is not possible to perform a full-scale experiment during the reconstruction of road traffic accidents, or an analytical investigation of a road traffic accident is required, for example, for educational purposes.

3. Conclusion
Thus, the experimental study confirmed the hypothesis formulated concerning the regularity of influence of a combination of factors on the formation of values of the steady-state deceleration and its rise time for vehicles of category M₁, wherein the correction coefficients and mathematical models are practically significant in terms of the improved accuracy and reliability of expert investigation during the reconstruction of road traffic accidents.

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