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Regarding the issue of the influence of factors on the braking parameters of M_1 category vehicles with electric or hybrid power unit

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Annotation. Problem. *The relevance of this work is explained by the fact that there are no works at all in the reference and normative literature on the theory and practice of forensic auto technical examination, and even more so, methodical recommendations regarding the values of the braking parameters of vehicles of the M_1 category with an electric power plant.* ***Goal.*** *The purpose of the work is to establish the factors that affect the braking parameters of M_1 category vehicles with an electric or hybrid power unit.* ***Methodology.*** *The approaches adopted in the work to solve the set goals are based on the theory of conducting the experiment, the theory of the interaction of the pneumatic tire with the road surface, the theory of the car and the laws of theoretical mechanics.* ***Results****. On the basis of the obtained experimental data regarding the value of permanent deceleration and the time value of the increasing deceleration during emergency braking of the M_1 category vehicles with an electric or hybrid power unit, the tasks will be solved necessary for conducting forensic engineering and transport examinations for specific road traffic events with the participation of M_1 category vehicles with an electric or hybrid power unit.* ***Originality****. The results of the study provided an opportunity to get an idea of the influence of factors on the braking parameters of M_1 category vehicles with an electric or hybrid power unit.* ***Practical value****. The obtained results can be recommended to forensic experts when writing expert opinions or expert studies.*

Key words: *braking efficiency, electric vehicle, M_1 category vehicle, adhesion utilized, braking rate, deceleration.*

Introduction

In the conditions of a large shortage of energy resources, intensive environmental pollution and global economic crisis phenomena, innovative means of transport such as electric vehicles are one of the most promising types of transport that are in demand among the population of different countries of the world. The use of electric vehicles on public roads does not guarantee complete road safety, therefore such vehicles are increasingly involved in traffic accidents.

The investigation of road traffic events for the trial of administrative, criminal and civil cases requires clarification of the braking parameters of M_1 category vehicles with an electric or hybrid power unit, since there are no clear guidelines in the well-known methodological recommendations used by research centers, institutes and investigative agencies clarification regarding the adoption of physical parameters for calculating the braking distance of an electric vehicle. In this regard, there is a need to conduct research on the braking process of vehicles of category M_1 with an electric or hybrid power unit, which will allow to determine its deceleration during emergency braking.

Analysis of publications

The process of vehicle braking is a complex physical phenomenon that is not permanent and depends on many factors that limit the potential effectiveness of the vehicle's braking system.

So, in work [1], the study of the braking efficiency of the vehicle was considered as a complex problem, which was solved due to the formation of the theory of weight distribution between the axles of the vehicle. This concept made it possible to establish a relationship with the main geometric parameters of the vehicle and its braking efficiency. And it also allows you to calculate the amount of vehicle deceleration based on the coordinates of the center of gravity of the vehicle and the parameters of the interaction of the tires of its wheels with the road surface.

In the work [2], the author established the influence of the characteristics of the composition of its axles with double or triple tires on the braking efficiency of the vehicle, thus it was shown and experimentally proven that the magnitude of the vehicle deceleration is influenced many other factors, in addition to the geometric and weight parameters of the vehicle.

The authors of the works [3, 4] note that a comprehensive assessment of the vehicle braking efficiency is a necessary condition for determining its braking distance, especially in the conditions in traffic accidents.

Therefore, the study of the braking efficiency of vehicles of the M_1 category with an electric or hybrid power unit is an actual study that requires detailed consideration.

Purpose and Tasks

The purpose of the work is to determine the amount of permanent deceleration of an M_1 category vehicle with an electric or hybrid power unit during emergency braking.

To achieve the set goal, it is necessary:

- to consider the theoretical aspects of braking of the M_1 category vehicle and to determine the main factors affecting the amount of vehicle deceleration;
- conduct experimental studies of the braking efficiency of M_1 category vehicles with an electric or hybrid power unit;
- to analyze the results of experimental studies of braking efficiency of M_1 category vehicles with an electric or hybrid power unit;
– propose an equation for determining the amount of deceleration of a M_1 category vehicle with an electric or hybrid power unit.

Theoretical aspects of vehicle braking of category M_1

It is known that the braking process of a wheeled vehicle is characterized by the magnitude of its deceleration, which is determined by the vehicle braking rate.

This phenomenon vehicle be described by equation (1) [1, 2] according to the scheme shown in Figure 1 [1, 2, 5], which is based on dividing the weight of the vehicle, conditionally into two parts.

$$z = \frac{f_1 \cdot b_g^{2\_axles} + f_2 \cdot a_g^{2\_axles}}{L_{(1,2)}^{2\_axles} - h_g \left(f_1 - f_2 \right)}, \qquad (1)$$

where $a_g^{2\_axles}$, $b_g^{2\_axles}$ and h_g – respectively, the coordinates of the location of the center of gravity of the wheeled vehicle relative to the front axle, the rear axle and the height of the location of the center of gravity above the level of the road surface, m;

f_1 and f_2 – adhesion utilized between the tire and the road surface, respectively for the tires of the front and rear axles (defined as: $f = R_x / R_z$);

$L_a = L_{(1,2)}^{2\_axles} = a_g^{2\_axles} + b_g^{2\_axles}$ – wheel base of the vehicle, m.

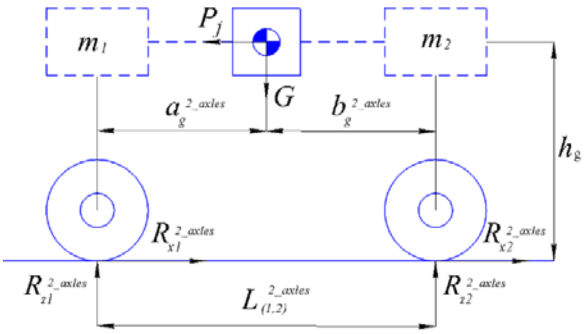

Fig. 1. Scheme of a two-axle wheeled vehicle (the weight of the vehicle is divided into two conventional parts m_1 and m_2) [2, 5]

As the analysis of scientific and technical literature [6–15] shows, the result of solving equation (1) varies depending on the mode of movement of the wheels of the vehicle:

- traction mode of movement

$$j_x = g \cdot z = g \cdot f\left(f_0\right);$$

- braking mode (in case of wheel slip S < 100 %).

$$j_x = g \cdot z = g \cdot f\left(f_x\right);$$

- braking mode (in case of wheel slip S =100 %).

$$j_x = g \cdot z = g \cdot f\left(f_{\text{тр}}\right).$$

In traction mode, the braking rate of the vehicle is practically equal to the average value of the coefficient of rolling resistance $(z \cong f_0)$ of all wheels of the car, if the forces of air resistance and friction forces in the elements of the chassis and transmission are neglected.

In the braking mode, under the condition that the tires of the vehicle wheels are slipping S = 100%, the braking rate of the vehicle is equal to the adhesion utilized of the locked wheel (the friction coefficient of the locked wheel or the coefficient of sliding friction) $z \cong f_{tr}$.

In the braking mode, under the condition that the wheels of the vehicle slip <100%, since the inequality $z \neq f_i \neq f_{tr}$, is practically always fulfilled, the braking rate of the vehicle is determined by the adhesion utilized of the corresponding axles of the vehicle and the geometric location of its center of gravity in the vertical plane relative to the road surface, as well as horizontal plane relative to the points of contact of car tires with the road surface [1, 4, 8, 11, 13] (Of course, this is true only under the condition of neglecting: air resistance forces and friction forces in elements of the chassis and transmission).

The analysis of scientific and technical literature [1 - 4, 9 - 15] showed that the value of the adhesion utilized is not a constant value. The authors of these works show that the adhesion utilized of the tire to the road surface increases with a decrease in the vertical load on the tire and decreases with an increase in the speed of the vehicle or an increase in the pressure in the pneumatic tire.

As for the effect of the coordinates of the center of gravity (a_g, b_g and h_g) on the amount of vehicle deceleration, this issue is almost not considered in scientific publications, although there are works [1, 2, 5] in which they affect the results of research and general conclusions research.

Description of technical parameters of devices, machinery and equipment

One of the most common devices for determining the deceleration of wheeled vehicles during road tests in expert practice is the decelerometer of the "MAHA" company VZM-300 [1] (Fig. 2), which is based on a single-coordinate accelerometer and has state metrological certification. The technical characteristics of the VZM-300 device are listed in Table 1.

According to the rules 71/320/EWG (which replaced 98/12/EG), the efficiency of the brake system of a wheeled vehicle is determined by measuring its average constant deceleration.

Fig. 2. Decelerometer of the "MAHA" companyVZM-300

Table 1. Technical characteristics of the VZM-300 "MAHA" decelerometer

№	Device parameter	Value
1.	Deceleration display limits, m/s^2	0-22
2.	Memory, RAM	128
3.	NiHM battery 8Ah supply voltage, V	6

The decelerometer VZM-300 calculates the average constant deceleration of the vehicle in one measurement based on the official requirements of ISO/DTR 13487F, in addition, the VZM-300 also meets the requirements of 71/320/EWG.

The error of the values of the constant deceleration of the vehicle obtained using the VZM-300 device, according to its technical characteristics, is no more than 0.1 m/s^2.

When performing experimental studies of the braking efficiency of vehicles of the M_1 category with an electric or hybrid power unit, the material and technical means listed in Table 2 were used.

Table 2. Material and technical means used in experimental research

№	Designation	Number of units
1.	M_1 category vehicles with an electric or hybrid power unit	7
2.	Decelerometer *VZM-300*	1
3.	Camera *Canon EOS M100*	1
4.	Building level (length 1m)	1

During the experimental research, all vehicles were in a technically sound condition [2].

The types of vehicles of the M_1 category with an electric or hybrid power unit that were studied differ from each other in weight and geometric parameters and belong to different classes of passenger cars, this was done in order to obtain an objective assessment of the braking efficiency of these cars in the same road conditions.

The following cars were used as M_1 category vehicles with an electric or hybrid power unit:

1) Electric car Tesla Model 3 Dual Motor Performance (Fig. 3), the characteristics of which are given in table 3.

This car uses an energy recovery system, which on average allows you to get an additional 50% of the battery charge from a full battery charge.

Fig. 3. Appearance of the electric car Tesla Model 3 Dual Motor Performance

Table 3. Technical characteristics Tesla Model 3 Dual Motor Performance

Full weight, kg	1931
Length, m	4,694
Width, m	1,850
Height, m	1,443
Wheel base, m	2,875
The dimensions of the tires of the wheels	235/35 R19/20
Driving wheels	all (4x4)
Unit power, kW	357,5
Unit torque, Nm	660
Battery, kW*h	82,0 (AWD)
Range, km	470-504

2) Electric car Audi E-Tron (Fig. 4), the characteristics of which are given in table 4.

The car uses an energy recovery system, which on average allows you to get an additional 30% of battery charge from a full battery charge.

Fig. 4. Electric car Audi E-Tron

Table 4. Technical characteristics of an electric car Audi E-Tron

Full weight, kg	2445-2695
Length, m	4,901
Width, m	1,935
Height, m	1,616
Wheel base, m	2,928
The dimensions of the tires of the wheels	255/50 R20
Driving wheels	all (4x4)
Unit power, kW	300
Unit torque, Nm	664
Battery, kW*h	95,0 (AWD)
Range, km	400

3) Electric car BMW i3 (Fig. 5), the characteristics of which are given in table 5.

Fig. 5. Electric car BMW i3

The car uses an energy recovery system, which on average allows you to get an additional 15-20% of battery charge from a full battery charge.

Table 5. Technical characteristics BMW i3

Full weight, kg	1195-1390
Length, m	4,000
Width, m	1,775
Height, m	1,570
Wheel base, m	2,570
The dimensions of the tires of the wheels	155/70 R 19
Driving wheels	Rear
Unit power, kW	125
Unit torque, Nm	250
Battery, kW*h	42,2 (120 A h)
Range, km	300

4) Electric car Volkswagen E-Golf (Fig. 6), the characteristics of which are given in table 6.

Fig. 6. Electric car Volkswagen E-Golf

Table 6. Technical characteristics electric car Volkswagen E-Golf

Full weight, kg	1605
Length, m	4,270
Width, m	1,799
Height, m	1,450
Wheel base, m	2,637
The dimensions of the tires of the wheels	205/55 R 16
Driving wheels	front
Unit power, kW	85
Battery, kW*h	36
Range, km	175

The car uses an energy recovery system, which on average allows you to get up to 15% of the battery charge from a full battery charge.

5) Electric car Nissan Leaf (Fig. 7), the characteristics of which are given in table 7.

Fig. 7. Electric car Nissan Leaf

Table 7. Technical characteristics Nissan Leaf

Full weight, kg	1521
Length, m	4,445
Width, m	1,770
Height, m	1,550
Wheel base, m	2,700
The dimensions of the tires of the wheels	205/55 R 16
Driving wheels	front
Unit power, kW	80
Unit torque, Nm	280
Range, km	160

The car uses an energy recovery system, which on average allows you to get up to 10% of the battery charge from a full battery charge.

6) Hybrid car Toyota Prius (Fig. 8), the characteristics of which are given in table 8.

Fig. 8. The appearance of a hybrid car Toyota Prius

Table 8. Technical characteristics Toyota Prius

Full weight, kg	1495
Length, m	4,480
Width, m	1,745
Height, m	1,490
Wheel base, m	2,700
The dimensions of the tires of the wheels	195/65 R 15
Driving wheels	front
Unit power, kW	72
Unit torque, Nm	142

The Toyota Prius hybrid car is equipped with a gasoline and electric unit, which allowed to reduce the level of harmful emissions and minimize fuel consumption.

7) Hybrid car Mitsubishi Outlander PHEV (Fig. 9), the characteristics of which are given in table 9.

Fig. 9. The appearance of a hybrid car Mitsubishi Outlander

Table 9. Technical characteristics Mitsubishi Outlander

Full weight, kg	2210
Length, m	4,655
Width, m	1,800
Height, m	1,680
Wheel base, m	2,670
The dimensions of the tires of the wheels	235/60 R 18
Driving wheels	all (4x4)
Unit power, kW	98
Unit torque, Nm	195

Mitsubishi Outlander PHEV equipped with a hybrid gasoline-electric unit capable of working both in series and in parallel modes. Unlike other hybrid cars, it is driven by the electric part of the hybrid installation with a total power of 120 kW, 60 kW on each of the car's axles.

Electric energy for the hybrid installation is obtained from a lithium-ion battery with a capacity of 12 kWh. In EV Drive Mode, the Mitsubishi Outlander PHEV can travel up to 50 km.

When driving for a long time at high speeds, the hybrid power plant works in Parallel Hybrid mode. In this mode, the gasoline internal combustion engine is connected to the front wheels of the car through a single-stage gearbox and provides most of the traction force.

Experimental studies of the braking process of an M_1 category vehicle with an electric or hybrid power unit

Research on the effectiveness of vehicle braking was conducted on a flat horizontal section of a highway with an asphalt concrete surface. Experimental determination of sustained deceleration of vehicles of category M_1 with electric or hybrid power unit was carried out on a dry surface. The road section met the standard conditions for the operation of vehicles: the longitudinal uphill of the road surface did not exceed 0.05%; transverse slopes were no more than 1%. The length of the road surface section was sufficient for acceleration and braking of vehicles.

During the research, a number of decelerogram (brake diagrams) of the vehicle braking process were obtained, some of which are presented in Figures 10-16.

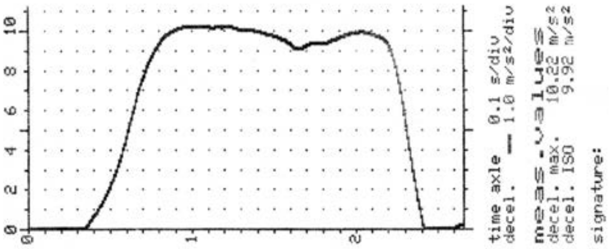

Fig. 10. Decelerogram of the braking of the Tesla Model 3 Performance electric car from a speed of 61 km/h

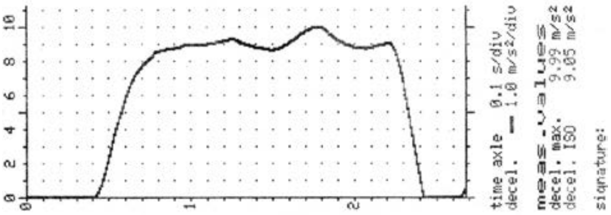

Fig. 11. Decelerogram of the braking of the Audi E-Tron electric car from a speed of 57 km/h

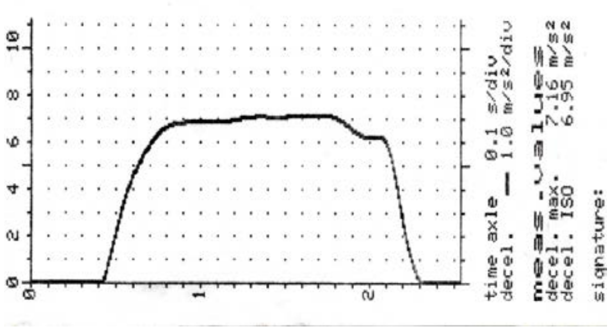

Fig. 12. Decelerogram of the braking of the BMW I3 electric car from a speed of 41 km/h

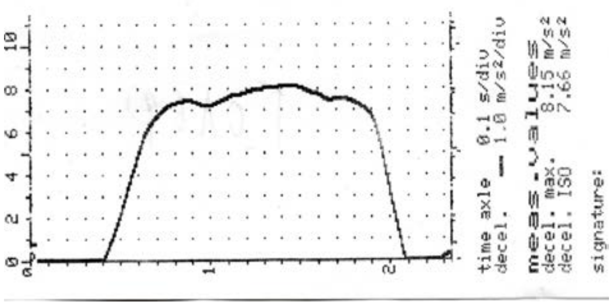

Fig. 13. Decelerogram of the Volkswagen E-Golf electric car braking from a speed of 39 km/h

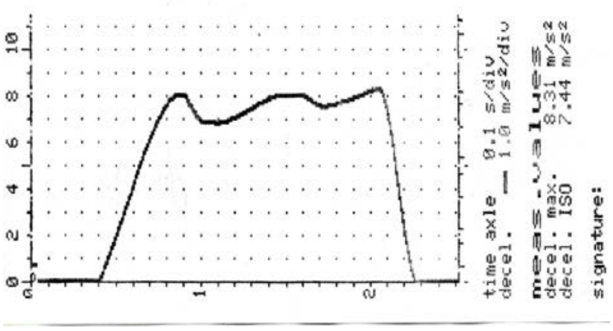

Fig. 14. Decelerogram of the braking of the Nissan Leaf electric car from a speed of 42 km/h

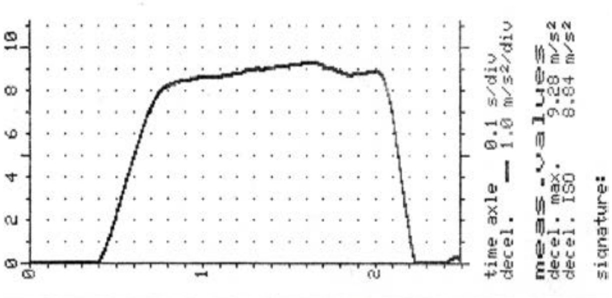

Fig. 15. Decelerogram of Toyota Prius hybrid car braking from a speed of 51 km/h

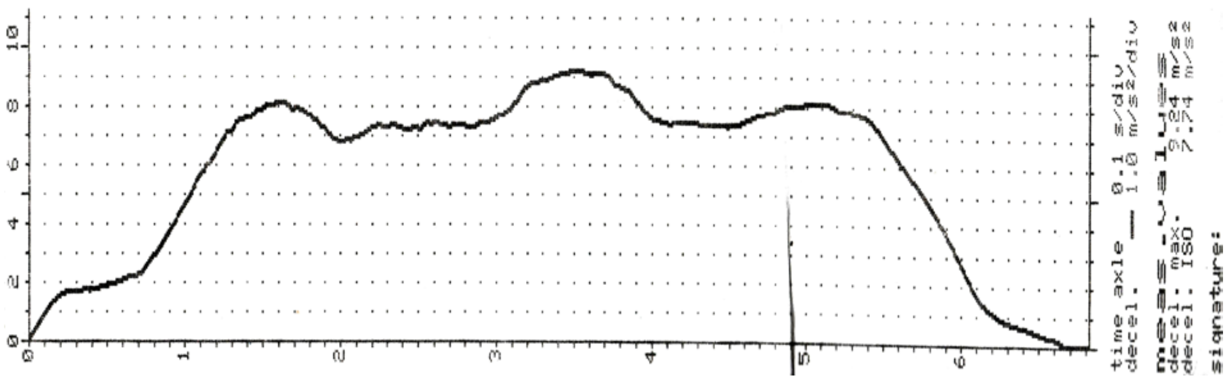

Fig. 16. Decelerogram of the braking of the Tesla Model 3 Performance electric car from a speed of 150 km/h

The obtained decelerograms show in numerical values the obtained maximum deceleration of the car and the average value of the deceleration for the entire braking process of the car according to the ISO-TR 13487 standard.

After processing the obtained braking decelerograms of the investigated vehicles, average deceleration values for vehicles with the corresponding wheelbase were obtained.

The results of calculating the average value of constant deceleration for the corresponding vehicles of the M_1 category with an electric or hybrid power unit are listed in Table 10 for the convenience of analysis.

Table 10. Results of experimental research of the average value of the constant deceleration of vehicles of category M_1, in m/s^2

V_a, km/h / L_a, m	20	60	100	140	160
2,57	6,84	6,52	6,20	5,88	5,72
2,637	7,65	7,30	6,94	6,58	6,40
2,67	7,63	7,28	6,92	6,57	6,39
2,7	8,34	7,95	7,56	7,17	6,98
2,875	9,23	8,80	8,37	7,94	7,72
2,928	9,33	8,90	8,46	8,03	7,81

Processing results of experimental research

To process the obtained results of experimental research of the average value of the steady deceleration of vehicles of the M_1 category with the appropriate wheelbase, we will use Listing 1 developed for the MATLab program.

Listing 1. Code of the program for calculating the value of the constant deceleration of a vehicle of category M_1 with an electric or hybrid power unit

```
clc; clear;
V=20:(160-20)/7:160;
L=[2.57 2.637 2.67 2.7 2.875 2.928];
[Va, La] = meshgrid(V, L);
ja=[6.84 6.72 6.52 6.36 6.20 6.04 5.88 5.72;
    7.65 7.52 7.30 7.12 6.94 6.76 6.58 6.40;
    7.63 7.50 7.28 7.10 6.92 6.74 6.57 6.39;
    8.34 8.19 7.95 7.75 7.56 7.36 7.17 6.98;
    9.23 9.07 8.80 8.59 8.37 8.16 7.94 7.72;
    9.33 9.17 8.90 8.68 8.46 8.25 8.03 7.81];
surf(Va, La, ja)
```

Based on the launch of the program presented in the form of Listing 1, we will get a three-dimensional surface (Fig. 17), which characterizes the change in the average value of the constant deceleration of vehicles of category M_1 with an electric or hybrid power unit, depending on the initial braking speed of the car (V_a) and its wheelbase (L_a).

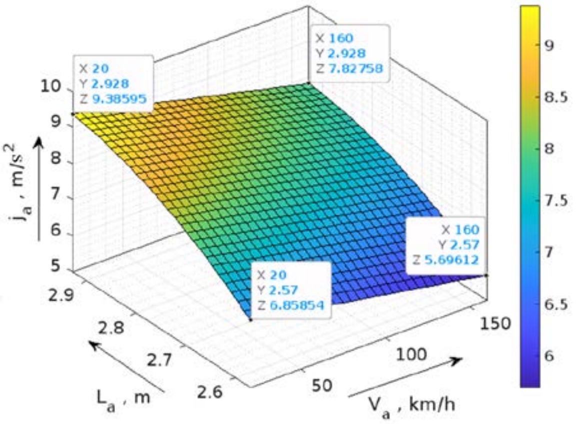

Fig. 17. Change in the average value of permanent deceleration of vehicles of category M_1 with an electric or hybrid power plant depending on the initial braking speed of the car (V_a) and its wheelbase (L_a)

With the help of the "Curve fitting" module, which is an add-on to MATLab, it is not difficult to approximate the data of a three-dimensional graph and obtain equation (2), which with a small error will allow you to determine the value of the constant deceleration of a vehicle of category M_1 with an electric or hybrid power unit, depending on initial braking speed of the car and its wheelbase.

$$j_a = 0.01 \cdot V_a \cdot (1 - L_a) + 80 \cdot L_a - 13 \cdot L_a^2 - 112. \quad (2)$$

The conducted research comparing the results of the calculation according to equation (2) with the real data of experimental studies of wheeled vehicles (Fig. 10 - 16) showed that the calculation error of the average value of vehicle deceleration does not exceed the average value of 5.5% for the accepted sample of vehicles under investigation.

Conclusion

Research into the braking dynamics of vehicles of the M_1 category with an electric or hybrid power unit showed that when determining the circumstances of a traffic accident involving such vehicles, when determining the amount of their deceleration, it is necessary to take into account not only the initial speed of their braking before the collision, but also the geometric parameters (wheelbase of the vehicle) because it significantly affects the amount of car deceleration.

For the accepted sample of investigated vehicles, the calculation error of the average deceleration value of a vehicle of category M_1 with an electric or hybrid power unit depending on the initial braking speed of the car (Va) and its wheel base (La) does not exceed the average value of 5.5%.

The influence of the initial braking speed of the car on the value of the average deceleration value of the M_1 vehicle with an electric or hybrid power unit is linear, unlike the influence of the wheelbase, which is subject to a quadratic equation.

Conflict of interests

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

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Щодо питання впливу факторів на параметри гальмування транспортних засобів категорії М1 з електричною або гібридною силовими установками

Анотація. Проблема. *Актуальність даної роботи пов'язана з тим, що в довідково-нормативній літературі з питань теорії та практики судової автотехнічної експертизи взагалі відсутні будь-які роботи, а тим більше, методичні рекомендації стосовно значень параметрів гальмування транспортних засобів категорії* M_1 *з електричною силовою установкою.* ***Мета.*** *Метою роботи є встановлення факторів, які впливають на параметри гальмування транспортних засобів категорії* M_1 *з електричною та гібридною силовими установками.* ***Методологія.*** *Підходи, що прийняті в роботі для рішення поставлених цілей, базуються на теорії проведення експерименту, теорії взаємодії пневматичної шини з поверхнею дорожнього покриття, теорії автомобіля та законах теоретичної механіки.* ***Результати.*** *На основі отриманих експериментальних даних відносно величини сталого сповільнення та величини часу наростання сповільнення при екстреному гальмуванні транспортних засобів категорії* M_1 *з електричною та гібридною силовими установками, буде розраховуватись величина зупинного шляху та будуть вирішуватись інші задачі, необхідні в процесі проведення судових інженерно-транспортних експертиз за конкретними дорожньо-транспортними пригодами за участі транспортних засобів категорії* M_1 *з електричною та гібридною силовими установками.* ***Оригінальність.*** *Результати дослідження надали можливість отримати уявлення про вплив факторів на параметри гальмування транспортних засобів категорії* M_1 *з електричною та гібридною силовими установками.* ***Практичне значення****. Отримані результати можуть бути рекомендовані судовим експертам при написанні висновків експерта та експертних досліджень.*

Ключові слова: *ефективність гальмування, електромобіль, транспортний засіб категорії* M_1*, реалізоване зчеплення, коефіцієнт гальмування, уповільнення.*

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