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INFLUENCE OF LOAD ON THE BRAKING PROPERTIES OF A SEMI-TRAILER TRUCK

Summary. This paper presents the results of an experimental study of the influence of the mass of the load on the variation of the longitudinal braking deceleration of a semi-trailer truck. Data were also obtained on the magnitude of braking decelerations under specific conditions. When investigating road accidents in the conditions of Bulgaria, no data are available in the specialized literature on the maximum braking decelerations of semi-trailer trucks, and the same can be said of the influence of the full mass of the vehicle on the braking properties. Such data are extremely important in expert evaluation of court cases. Traffic safety is one of the main factors for preserving human health and life. Bulgaria has a relatively high number of deaths as a result of traffic accidents among countries in the European Union. Thus, the problem is very relevant for this country. One of the main factors determining traffic safety is the braking properties of vehicles and, more specifically, the braking deceleration.

1. INTRODUCTION

Road safety in Bulgaria is at a very low level compared to some European countries. The number of people killed in road accidents relative to the population is three to four times higher than the leading European countries. According to data from the Bulgarian road police, in 2023, there were 6,983 serious traffic accidents in which 524 people died and 9,080 road users were injured. Compared to 2022, there were 374 more serious traffic accidents in 2023.

In recent years, the share of road transport in the country has increased significantly at the expense of other modes of transport. This has led to a number of problems related to traffic safety. In addition to the braking properties of vehicles, road safety also depends on the serviceability of the suspension system [1]. The braking properties of electric cars are also interesting. In [2], the dynamic and braking properties of electric cars in different modes were analyzed. The braking process of vehicles is also directly related to the tire-road friction coefficient of the tires to the road [3]. Some authors [4] have investigated the dynamic and braking properties of light vehicles. Other authors [5] investigated

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the dynamic and braking properties depending on the type of vehicle. Braking capabilities are highly dependent on the characteristics of brake pad surfaces, which were investigated in [6]. According to [7], braking performance studies are of the utmost importance in accident reconstruction evaluation. Vehicle braking performance is also directly responsible for pedestrian accidents, as discussed in [8, 9].

One specific problem is road traffic accidents with trucks. In [10, 11], the braking performance of trucks were investigated. For expert research of this problem, data for actual vehicle braking properties are required. Such data on road conditions are missing in the Bulgarian specialized literature. There is also no data on the influence of the vehicle's mass on its braking properties and the length of the braking distance. This gives rise to the need to conduct experimental studies in real road conditions to obtain modern data on braking decelerations and to evaluate the influence of the mass of the transported load during emergency braking.

Vehicles are stopped mainly with the brakes when the clutch is disengaged. Brakes create a braking torque on the wheels, hindering or completely stopping their rotation. As a result of the friction in the brakes and between the tires and the road when the wheels block, the vehicle's kinetic energy when braking is converted into heat, which is dissipated into the atmosphere.

The engine is also used to stop the vehicle, in which case the crankshaft is forced to rotate by the drive wheels. Engine braking can be applied alone or in conjunction with the brakes.

The braking effect on the vehicle is also exerted by the resistance forces of the movement – namely, road resistance and air resistance.

The ability of a vehicle to forcibly reduce its speed and stop quickly is an important dynamic property that has a significant impact on traffic safety. To ensure safe movement at high speeds, an effectively functioning braking system is necessary.

The following indicators are used to evaluate the braking properties of a vehicle: the maximum linear deceleration that can be obtained when braking in given road conditions, the minimum braking distance by the vehicle from the start to the end of the stop, and the stopping time during which the vehicle covers the minimum stopping distance [12]. These indicators are determined when the vehicle stops with the clutch disengaged. In this case, the engine does not affect the braking.

The balance of forces that act on the car when braking on an incline is expressed by the following equation:

$$F_a = F_C + F_f \pm F_i + F_B, \tag{1}$$

where F_C is the total braking force applied to the contact surface of the wheels with the road. The plus sign in front of the force F_i refers to uphill and the minus sign to downhill.

Since the speed of movement decreases rapidly when stopping, the air resistance F_B also decreases and can be neglected. In addition, the rolling resistance F_f on a road with a hard surface in good condition is small, and when braking with full braking, the wheels do not roll at a high rotational speed, and this force can be assumed to be 0.

The maximum linear deceleration is created when a maximum braking force F_{cmax} is applied to the wheels of the vehicle. With a working brake system, the maximum braking force is limited by the grip of the wheels on the road. In vehicles, brakes are applied to all wheels. Therefore, the entire weight participates in the traction with the road to obtain a braking force, which is expressed by the following equation:

$$F_{cmax} = G\varphi\cos\alpha, \tag{2}$$

where φ – the friction coefficient; α – the slope angle of the road, G – the weight of the vehicle (N).

2. EQUIPMENT AND METHODS

The research used a set of Tractor Scania R420 LA HNA and Gondola Semi Trailer vehicles (Fig. 1). The first registration of the Tractor Scania R420 LA HNA was in 2010.

The tractor Scania R420 is a category N3 vehicle (motor vehicles designed and constructed mainly for the transport of goods with a technically permissible maximum mass over 12 t). The semi-trailer is a category O4 vehicle (trailers designed and constructed for the transport of goods with a technically permissible maximum mass of more than 10 t).

The cargo is stone fraction. The mass of the tractor is 7435 kg. The semi-trailer has a mass of 6285 kg. The total mass of the vehicle composition is 43,180 kg. The load has a mass of 29,460 kg.

The speed at the beginning of a stop is 40–60 km/h, which is in accordance with safety in view of the large mass of the vehicle and the real road situation.

According to [13], the permissible maximum mass for movement on the roads in Bulgaria of a two-axle motor vehicle with a three-axle trailer is 40 t. It is common practice in Bulgaria to exceed the permissible weight by a small amount, and the carrier pays a toll for this. In specific studies, the permissible mass of the vehicle was exceeded by 3180 kg.

Fig. 1. Tractor Scania R420 LA HNA and Gondola Semi Trailer

Tractor tires are Laufenn brand 385/65R22.5 DOT 1023. Semi-railer tires are Sailun brand 385/65R22.5 DOT 0822.

The tests were conducted on a dry asphalt surface on the republican and municipal road network of Bulgaria. Fig. 2 shows a photograph of the road and the brake marks created during braking.

Fig. 2. Road surface and brake marks

Some authors [14] have used GPS-based systems for research related to the braking and dynamic properties of vehicles. VB20SL 20Hz GPS Data Logger from Racelogic [15] was used to register the data. It is highly accurate given the requirements for the preparation of quality expertise for the police and the court.

The main features of the VBOX20 SL receiver are as follows: 20 Hz non-contact speed and distance measurements via GPS, measurement of slip angle and deflection level, measuring the angle of or roll angle, two analog outputs, 2 x 24-bit digital outputs, a "Brake" sensor or "Event trigger" input, CAN interface data inputs and outputs, and RS232 serial interface.

The main parameters and characteristics recorded by the VBOX20 SL system are presented in Table 1.

Table 1

The main parameters and characteristics of the VBOX20 SL

Parameter	Characteristics
Speed	From 0.1 to 1609 km/h, dispersion 0.1 km/h
Distance	Accuracy 0.05%, scatter 0.001m
Acceleration	Up to 20 g, accuracy 0.5%, scatter 0.01 g

The results of the experimental trials were processed with Vbox Tools. This system provides highly accurate and convenient operation. Fig. 3 shows a real recording of the braking deceleration and the way the results are reported, including the average value of the marked area.

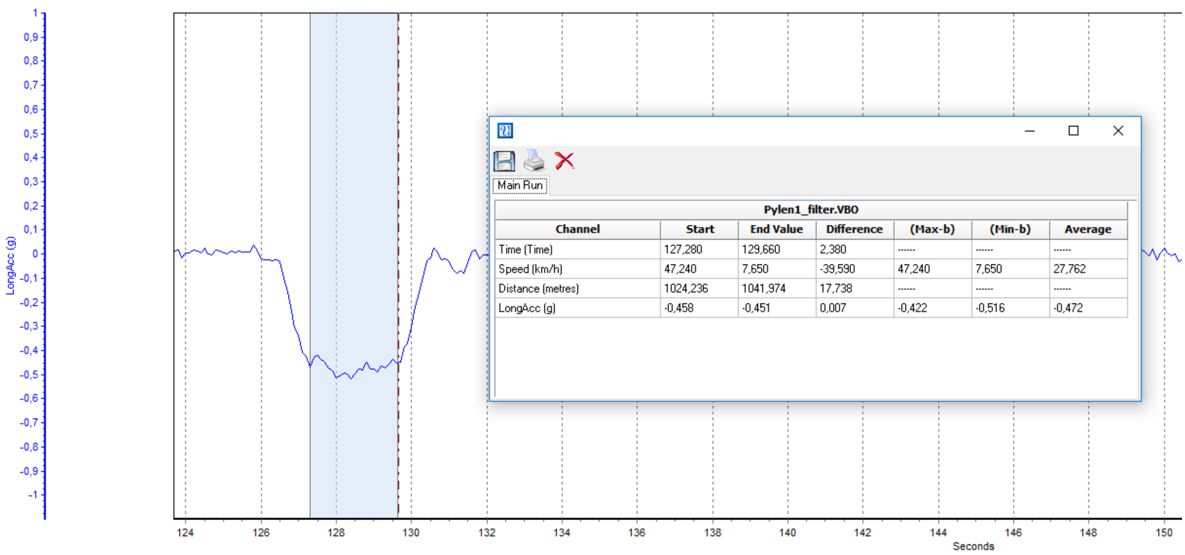

Fig. 3. Deceleration reporting area and additional data window

For the specific braking experience with maximum load, the following braking deceleration values were recorded in the marked area: minimum value = 0.422 g, maximum value = 0.516 g, and average value = 0.472 g.

3. RESULTS AND DISCUSSION

Figs. 4 and 5 present part of the real records of the change in acceleration during an emergency stop of the truck (unloaded and fully loaded, respectively).

All trials from the conducted research were processed using SPSS software. Table 2 presents the results for the main numerical characteristics of braking deceleration for the different braking conditions processed and expressed in g.

Statistical results of the main numerical characteristics for the deceleration of the fully loaded truck reveal an average value of 0.47 g; the smallest value obtained was 0.43 g, and the largest value obtained was 0.50 g.

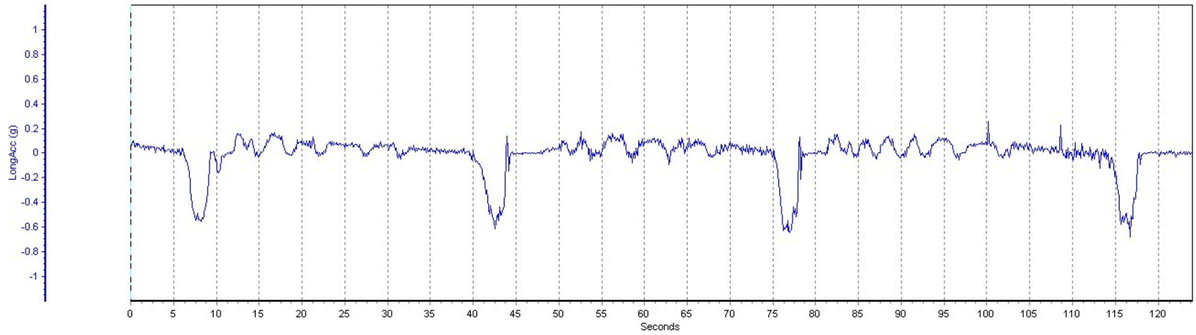

Fig. 4. Change in acceleration for an unloaded truck

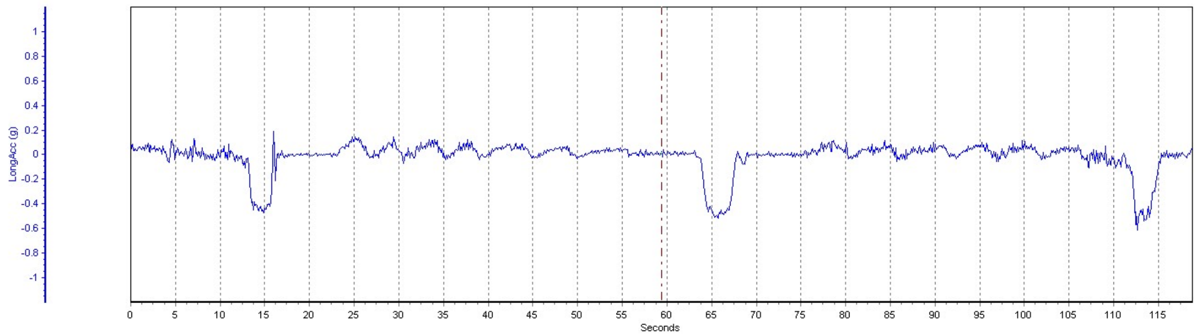

Fig. 5. Change in acceleration for a fully loaded truck

Table 2

Basic numerical characteristics of braking deceleration

Statistics		Fully loaded	Unloaded
N	Valid	10	10
	Missing	0	0
Mean		0.4709	0.5866
Median		0.4730	0.5960
Mode		0.43	0.53
Std. Deviation		0.02599	0.03125
Skewness		-0.444	-0.873
Std. Error of Skewness		0.687	0.687
Kurtosis		-0.770	-0.611
Std. Error of Kurtosis		1.334	1.334
Range		0.08	0.09
Minimum		0.43	0.53
Maximum		0.50	0.62

For an unloaded truck, the average value was 0.59 g, the smallest value was 0.53 g, and the largest value was 0.62 g.

A study on interval estimates was conducted in order to determine the confidence interval of the obtained results. The results for the interval estimates of the average braking deceleration values for the different conditions are presented in Table 3.

From the results for the interval estimates of the average accelerations under the different conditions, it follows that in 95% of the cases, these values would be between the specified limits.

In expert practice, when determining braking distances and other characteristics, accelerations and decelerations are presented in m/s^2. This has also been accepted by the police and the court. Therefore, the statistical processing of the results was done using this metric. Table 4 presents the results of the main numerical characteristics processed and expressed in m/s^2.

Table 3

Interval estimates of braking deceleration averages

Descriptives			Statistic	Std. Error
Unloaded	Mean		0.4709	0.00822
	95% Confidence Interval for Mean	Lower Bound	0.4523	
		Upper Bound	0.4895	
Fully loaded	Mean		0.5866	0.00988
	95% Confidence Interval for Mean	Lower Bound	0.5642	
		Upper Bound	0.6090	

Table 4

Basic numerical characteristics of braking deceleration

Statistics		Fully loaded	Unloaded
N	Valid	10	10
	Missing	0	0
Mean		4.6180	5.7540
Median		4.6700	5.8500
Mode		4.69	5.19
Std. Deviation		0.24818	0.30526
Skewness		-0.542	-0.881
Std. Error of Skewness		0.687	0.687
Kurtosis		-0.610	-0.605
Std. Error of Kurtosis		1.334	1.334
Range		0.73	0.87
Minimum		4.20	5.19
Maximum		4.93	6.06

Under this condition, a study was conducted on the interval evaluations, and the results for the different stopping conditions are presented in Table 5.

The lower and upper limits of the average braking deceleration values for the unloaded truck were 5.54 and 5.97 m/s^2, respectively. For a fully loaded truck, these limits were 4.44 and 4.80 m/s^2.

Table 5

Interval estimates of braking deceleration averages

Descriptives			Statistic	Std. Error
Unloaded	Mean		5.7540	.09653
	95% Confidence Interval for Mean	Lower Bound	5.5356	
		Upper Bound	5.9724	
Fully loaded	Mean		4.6180	.07848
	95% Confidence Interval for Mean	Lower Bound	4.4405	
		Upper Bound	4.7955	

The Law on Road Traffic in force in Bulgaria stipulates that drivers of road vehicles must, when choosing their speed, take into account the atmospheric conditions, the topography of the area, the condition of the road and the vehicle, and the load being transported, with the nature and intensity of the movement, with the specific conditions of visibility, to be able to stop in front of any foreseeable obstacle. Drivers are obliged to reduce their speed and, if necessary, stop when there is a danger to traffic.

When choosing the speed of the driver of a road vehicle for a category such as the examined car, it is forbidden to exceed the following speed values: 50 km/h in town and villages, 70 km/h outside town and villages, and 100 km/h on the highway.

The dangerous zone for stopping the truck was calculated by taking this into account and based on the obtained data on the braking deceleration in real road conditions. In the expert study of the possibility of preventing road accidents by drivers by braking, the danger zone was calculated according to the following equation:

$$S = (t_d + t_v)V + \frac{V^2}{2\varphi g}, \quad (3)$$

where t_d and t_v are the reaction times of the driver and the vehicle breaking system; V is the speed at the start of the stop; φ is the coefficient of friction between the tires and the road; and g is ground acceleration.

The driver's reaction time is the time from the moment a hazard appears in the driver's field of view to the beginning of its impact on the controls (pedals, steering wheel, etc.). This time mainly depends on the probability of an accident occurring in the created traffic situation and whether the driver had an opportunity to detect signs of possible danger in advance and determine with sufficient accuracy the place where the danger could have appeared. The driver's reaction time is within basic limits of 0.6 to 1.4 seconds. At this time, it can be inflated for different situations (e.g., at night).

The vehicle response time includes the time required for the actuating braking system and the time for the brake deceleration increase. The time for the braking system reaction is the interval from the start of pressing the brake pedal until the occurrence of a braking moment on the wheels. This time depends on the type of system, the wear of the parts in the system, and its adjustment. The time for the braking system reaction is mainly in the range 0.1 - 0.4 seconds.

The braking deceleration rise time is the interval from the occurrence of braking deceleration until reaching the maximum value. It depends on many factors, including the coefficient of friction, the load of the car, the magnitude of the speed at which braking begins, and the inertia moments of the rotating masses to the axis of the wheels. The rise time varies widely. For category M1 vehicles (passenger cars), when braking on a dry road, it is about 0.4 s, and for category N3 O4 vehicles (trucks), it is about 0.7 s. For the calculation of the danger zone, half of the magnitude of the braking deceleration rise time is taken.

The coefficient of friction is the ratio of the friction force to the normal reaction. The friction force represents the maximum possible frictional force (as an absolute value).

Table 6 presents the results for the length of the truck's braking distance for different speeds, calculated according to Equation 3. In the calculations, the total reaction time of the driver and the vehicle is 1.6 seconds, which corresponds to the road conditions and the type of vehicle.

Table 6

Length of braking distance for different speeds

Speed limit	Stopping distance, m	
	Fully loaded	Unloaded
Inside towns and villages (50 km/h)	43.10	39.00
Outside towns and villages (70 km/h)	72.00	63.97
Highway (100 km/h)	127.97	111.55

The fully loaded vehicle results show a 67% increase in the danger zone for stopping for the maximum permitted speed outside towns and villages compared to that inside towns and villages. For highways, the increase is 197% compared to inside towns and villages.

The results for the influence of the vehicle mass determine an increase in the danger zone with a full load compared to an unloaded vehicle as follows: inside towns and villages (50 km/h) – 11%; outside towns and villages (70 km/h) – 13%; highway (100 km/h) – 15%.

Fig. 6 presents the results for the length of the danger zone for different braking conditions.

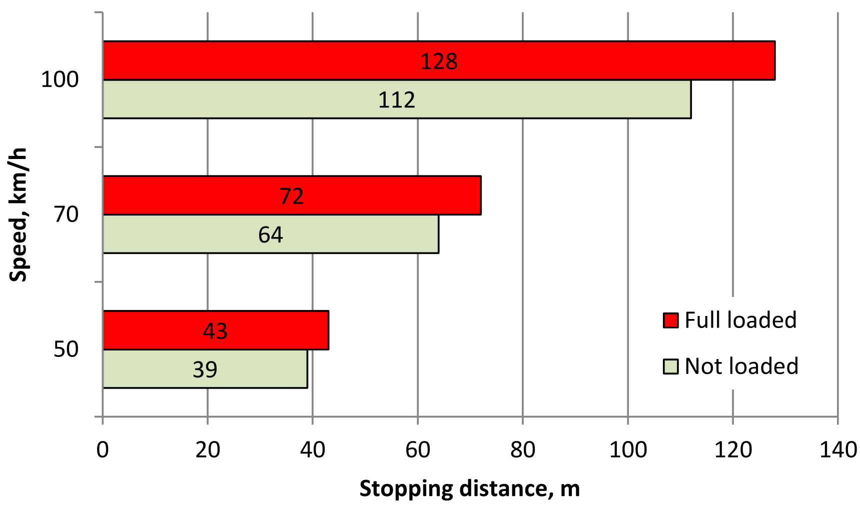

Fig. 6. Length of the danger zone

For traffic safety, it is particularly important to drive at a speed consistent with the distance of sight. It is also important to know the effect of vehicle mass on this speed. The reasonable speed is calculated by the following equation:

$$V_r = [\sqrt{(t_d + t_v)^2 + 2D/\varphi g} - (t_d + t_v)]\varphi g, \quad (4)$$

where t_d and t_v – the reaction times of the driver and the vehicle breaking system; D – the sight (visibility) distance; φ – the friction coefficient; g – ground acceleration.

Table 7 presents the results for the adjusted speed of the Tractor Scania R420 and semi-trailer depending on the sight distance calculated with the average braking deceleration values obtained from the experimental study.

The analysis of the reasonable speed depending on sight distance speed results shows that, assuming the same sight distance, if the vehicle is driven with a maximum load, the reasonable speed should be reduced by 7–8% (3.4–8.5 km/h) for the limits of the investigated sight distances in order to comply with the legal requirements and to ensure the necessary traffic safety.

Table 7

Reasonable speed depending on sight distance

Visibility distance, m	Reasonable speed, km/h	
	Fully loaded	Unloaded
40	47.54	50.90
50	55.22	59.34
60	62.23	67.08
70	68.73	74.26
80	74.82	80.99
90	80.56	87.34
100	86.01	93.37
110	91.21	99.13
120	96.18	104.65

4. CONCLUSIONS

Despite the measures taken to improve traffic safety on Bulgaria's roads, in 2023 there were 6,983 serious traffic accidents in which 524 road users died. Compared to the previous year, there were 374 more serious traffic accidents in 2023, which is an increase of about 6%.

Data on the braking deceleration of a truck for different braking conditions have been obtained experimentally. Statistical processing was performed, and the main numerical characteristics were determined.

For an unloaded truck, the average value of braking deceleration is 0.59 g (5.75 m/s^2), and for a fully loaded truck, the average value is 0.47 g (4.62 m/s^2). This reflects a 19.7% reduction in braking deceleration.

A study of the interval estimates was conducted and the confidence intervals of the obtained results were determined.

The lower and upper limits of the average values of the braking deceleration were established for an unloaded truck, the lower and upper limits of the average values of the braking deceleration are 5.54 and 5.97 m/s^2, and for a fully loaded truck, they are 4.44 and 4.80 m/s^2.

The danger zone during an emergency stop of the truck for different speeds and different masses has been determined.

The influence of vehicle mass on the length of the dangerous stopping zone was established. The results indicate an increase in the length of the danger zone with a fully loaded truck compared to unloaded truck as follows: inside towns and villages (50 km/h) – 11%; outside towns and villages (70 km/h) – 13%; highway (100 km/h) – 15%.

The influence of vehicle mass on the reasonable speed of movement for different sight distances was determined.

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