Effects of bulk cargo displacements on changes in truck axle loads

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Abstract. Changes in road legislation and trucking regulations have led to the need to take into account the maximum axle loads that arise during road transport. In particular, this task is relevant when transporting bulk cargo because when braking or accelerating trucks (road trains), when driving on a longitudinal gradient, or when driving on curves, there can be a displacement of part of the cargo relative to the axles of the vehicle. In article results of experimental research of displacements of loose cargo (gravel, crushed stone) at transportations and their influence on change of axle loadings of cargo vehicles are resulted. During the research the level of loose cargo in semitrailer truck-trailer before and after the experiment was measured, axle load weighing and full train weight weighing was made, in addition video recording of loose cargo displacement was made. Conducting the analysis of experimental data of axial weighing we found out that during transportation of loose cargo its redistribution inside semi-trailer takes place, and it in its turn leads to change of axle loads of road-train. The axle load variations were outside the measurement error range of 1.4 to 4.9%. A further proof of the shifting of the bulk load in the semi-trailer was the video recording of the load in transit. The analysis of the videos showed that both crushed stone and gravel shifted in the semitrailer when the vehicle was moving at high speed. As a result of this work, an experimental confirmation of the fact that the bulk cargo is shifted relative to the sides of the semi-trailer during braking and this shift leads to changes in the axle loads of trucks was obtained. Keywords: axle load, natural angle of slope, loose load, axle-based weighing, braking.

1 Introduction

Changes in road legislation and trucking regulations have led to the need to take into account the maximum axle loads that can occur during transport. This is particularly relevant for the transport of bulk goods because when trucks (combinations of vehicles) brake or accelerate, move down a slope or drive around corners, part of the load may shift relative to the vehicle axles [1, 2, 3]. This, in turn, can alter the axle loads of the truck. This problem is acute for carriers and has been little studied in the scientific literature. The available publications consider mainly the oscillating motion of the vehicle-load system,

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which occurs during braking, acceleration, taking into account the uneven profile of the roadway, and its impact on bridge supports or tanker trucks transporting liquids, as well as problems of transportation of bulk cargo by rail or water transport. This paper presents an experimental study of the effect of displacement of loose goods (gravel, crushed stone) occurring during braking moments on the change in axle loads of vehicles.

2 Materials and methods

A three-axle truck tractor with a three-axle semi-trailer was considered as a test object. Before conducting the experimental study, it was necessary to determine the parameters of the bulk cargo being transported, that is, determine its angle of natural slope, the value of which can be used to judge the mobility of the cargo. For this purpose, on an even horizontal surface (plywood sheet with area ~1 m^2) was set in height of 1 m with internal diameter d = 152 mm and the investigated loose material was poured in it. Then the cylinder was slowly lifted, letting the material freely fall onto a horizontal surface (Fig. 1). Then the base diameter D and height h of the resulting cone were measured and the angle of natural slope was determined according to the formula:

$$a' = arctg\ \frac{2h}{D-d} \tag{1}$$

Tests were carried out three times for each material: from two separate samples and a third prepared after averaging the first two.

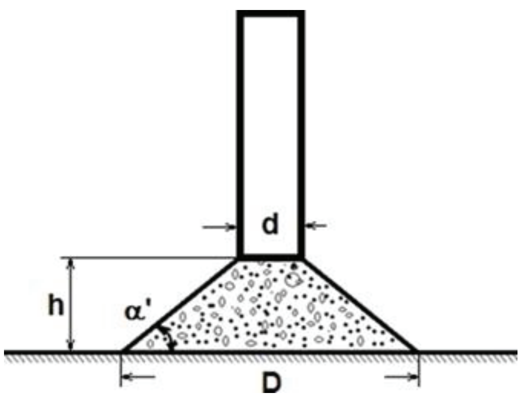

Fig. 1. Diagram for determining the angle of natural slope.

Next, cargo was poured into two identical semi-trailers. The first was filled with crushed stone of fraction 5-20 mm and weight 24.52 tons, the second - with gravel of fraction 5-20 mm and weight 25.96 tons. Then the total weight of each road train was weighed [4, 5, 6]. After that, the level of load in the semi-trailer was measured at the first axle weighing point. The load level in the semi-trailer was measured with a tape measure with an accuracy of ±1 cm along the sides, starting at the front of the right side, at intervals of 1 m from the upper point to the surface of the load. The level of the load was not measured on the rear wall and additional measuring points were added at 0.5 m intervals, one at the front of the left and right side of the semitrailer and similarly at the rear of the semitrailer (Figure 2). Then weighed along the axle on EVOCAR-2000-10 scale, which meets the requirements of "GSI: Non-automatic scales. Part 1. Metrological and technical requirements. Tests" GOST OIML R 76-1-2011. After the first axle weighing each semi-trailer was equipped with a video camera on the front left side.

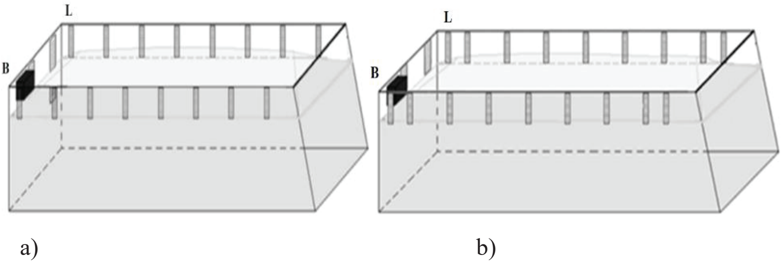

Fig. 2. Schematic diagram of measuring and fixing the load level (a - crushed stone, b - gravel) in a semi-trailer: B - video camera, L - measuring tool (tape measure).

A sharp braking speed of 90 km/h was then applied on road sections with a longitudinal gradient of 2-7%. The resulting acceleration was estimated using the formula:

$$a = \frac{\Delta V}{t}, \quad (2)$$

here ΔV is the change in speed of the road train, t is the time during which braking took place.

In addition, the brake friction coefficient for the road train system "asphalt concrete road surface" was determined according to the formula:

$$\mu = tg\alpha + \left(a + \frac{F_c}{m}\right) \cdot \frac{1}{g \cdot cos\alpha}, \quad (3)$$

here α is the longitudinal gradient of the road (in degrees), a is acceleration of the train at the moment of braking; $0.5 \cdot C_x \rho S \Delta V_1^2$ – air resistance, $C_x = 0.8$ is the aerodynamic drag coefficient for this type of truck, $\rho = 1.3$ kg/m^3 – is air density, S is the frontal projection area of the road train, m is the gross weight of the road train, g is the acceleration of gravity.

After braking, a second axle weighing of each road train was carried out and the level of load in the semi-trailers was measured. The shifting of the load in the semi-trailers was also recorded on the video cameras. Video recording of the shifting of the bulk cargo in the semi-trailers was carried out using GoPro video cameras during the movement of the road train from the first weighing station to the second weighing station [7, 8].

3 Results

Measurement of the natural slope angle showed that both loads have high internal friction and consequently low mobility of the load particles. The values of the angle of natural slope calculated by the formula (1) for crushed stone and gravel within the measurement error correspond to the data given in SNiP 2.05.07-91* and SP 22.13330.2011 and were 45° ± 5° for crushed stone and 42° ± 4° for gravel. Note that the mobility of the load was assessed on the basis of the condition:

$$a \geq g \cdot tg\alpha', \quad (4)$$

where a defines acceleration of the bulk cargo in the semi-trailer, g - acceleration of gravity.

Condition (4) shows that in order for the load to start shifting it is necessary to overcome the internal friction between the particles, which is determined by the natural angle of slope of the bulk cargo. At such values of the angle of natural slope the displacement of the bulk cargo was to be expected only at high accelerations of the road train (at least 5 m/s^2), which could be achieved by sudden braking or by braking when driving down a longitudinal slope of the road [9].

Experimental data and calculated by formulas (2) and (3) values of acceleration of road-train and coefficient of friction at the moment of braking are given in table 1. The values obtained indicate that in the experiment the conditions specified in the theoretical calculation were met, that is, in the theoretical calculation were used the values of acceleration at the time of braking for the train from 5 to 7 m/s^2, and the coefficient of sliding friction for rubber and dry asphalt taken equal to 0.75, guided by the fact that its minimum value should not be less than that value which was determined by the tyre grip class on the wet surface of the European label of tyres (C, E). A significant observation from this experiment was the slight skidding of the train during braking moments, if the acceleration of the train exceeded 8 m/s^2, this fact was indicated in the theoretical calculation [10].

Experimental data to determine the level of crushed stone and gravel in the semi-trailers showed insignificant changes in the load level in each semi-trailer, only at some points was there a noticeable difference between the load levels before and after braking. Mostly the load shift was to the right and front side. For example, in a trailer with crushed stone the level of the load changed by 3cm to the right and front side, and in a trailer with gravel the level at some points changed by 5-11cm to the right side. At other points the changes in load level were insignificant and within the limits of measurement error. These changes in gravel and crushed stone level in the semi-trailers are attributed to uneven loading, after which some of the load was shifted to the left side of each semi-trailer. It should be noted that there was no levelling of the loading surface immediately after loading as the objective was to approximate the experiment as closely as possible to the actual transport of goods. Therefore, only a qualitative assessment of load displacement can be made from the results of load level measurement [11, 12, 13, 14].

The results of gross vehicle weight and axle load weighing before and after the experiment are shown in Table 2, the readings of 12 EVOCAR scales installed under each wheel of the vehicle during axle load measurement and the weight control data obtained by the standard methodology used in determining whether a vehicle exceeds the permitted weight and the established axle load limits are given. It should be noted that the axle counting was taken from the cab of the vehicle during weighing. From the analysis of experimental data given in table 2 we can see that during transportation of bulk cargo its redistribution inside the semi-trailer takes place and this in its turn leads to change of axle loads of the road-train. So, for example, at transportation of broken stone according to the data of weight control, change of axle load of the road-train before and after the experiment on axles 2, 3, 5 and 6 exceeded 1.2 % and made 1.4, 1.7, 3.3 and 1.4 %. It should be noted that the most significant was the change in axle load on the 5th axle.

Table 1. Experimental data for measuring road train acceleration and friction coefficient during braking.

Brake location	Cargo	Slope α, %	Acceleration *a*, m/s²	Friction coefficient μ
Section 1	Crushed stone 5-20	7	5.0	0.62
Section 2	Gravel 5-20	5.6	8.3	0.91
Section 1	Gravel 5-20	7	6.1	0.69
Section 3	Gravel 5-20	2	9.3	0.97
Section 4	Gravel 5-20	4	8.0	0.85

Table 2. Data from the GVWR and axle train weighing experiment.

Weighing type	Object	Axle 1, kg	Axle 2, kg	Axle 3, kg	Axle 4, kg	Axle 5, kg	Axle 6, kg
Full weight	empty truck	18 040					
	load crushed stone 5-20	24 520					
	Total weight	42 560					
Axle based before the experiment	Right wheel	3230	3980	3590	3860	3920	3710
	Left wheel	3260	3170	3170	3930	3470	3290
	Total weight	6490	7150	6760	7790	7390	7000
		42 580					
Axle based after the experiment	Right wheel	3140	3700	3680	3780	3660	3680
	Left wheel	3280	3500	3200	3860	3580	3420
	Total weight	6420	7200	6880	7640	7240	7100
		42 480					
change, %	Right wheel	-2.9	-7.6	2.4	-2.1	-7.1	-0.8
	Left wheel	0.6	9.4	0.9	-1.8	3.1	3.8
	Axle load	-1.1	0.7	1.7	-2.0	-2.1	1.4
Weight control, axle based before the experiment	Axle load	6440	7120	6740	7520	7520	7080
	Error	80	80	80	80	80	80
	Total weight	42420 ± 480					
Weight control, axle based after the experiment	Axle load	6420	7220	6860	7500	7280	7180
	Error	80	80	80	80	80	80
	Total weight	42460 ± 480					
change, %	Axle load	-0.3	1.4	1.7	-0.3	-3.3	1.4
Full weight	Empty road train	17 520					
	Cargo gravel 5-20	25 960					
	Total weight	43 480					
Axle based before the experiment	Right wheel	3250	3560	3370	3890	3870	3570
	Left wheel	3340	3350	2980	4100	3870	4080
	Total weight	6590	6910	6350	7990	7740	7650
		43 230					
Axle based after the experiment	Right wheel	3320	3210	3180	3850	3560	3450
	Left wheel	3480	3770	3090	4150	3890	4150
	Total weight	6800	6980	6270	8000	7450	7600
		43 100					
change, %	Right wheel	2.1	-10.9	-6.0	-1.0	-8.7	-3.5
	Left wheel	4.0	11.1	3.6	1.2	0.5	1.7
	Axle load	3.1	1.0	-1.3	0.1	-3.9	-0.7
Weight control, axle based before the experiment	Axle load	6640	6920	6280	7960	7760	7700
	Error	80	80	70	100	80	100
	Total weight	43260 ± 510					
Weight control, axle based after the experiment	Axle load	6800	6980	6280	7980	7400	7540
	Error	80	80	80	100	80	100
	Total weight	42980 ± 520					
change, %	Axle load	2.4	0.9	0.0	0.3	-4.9	-2.2

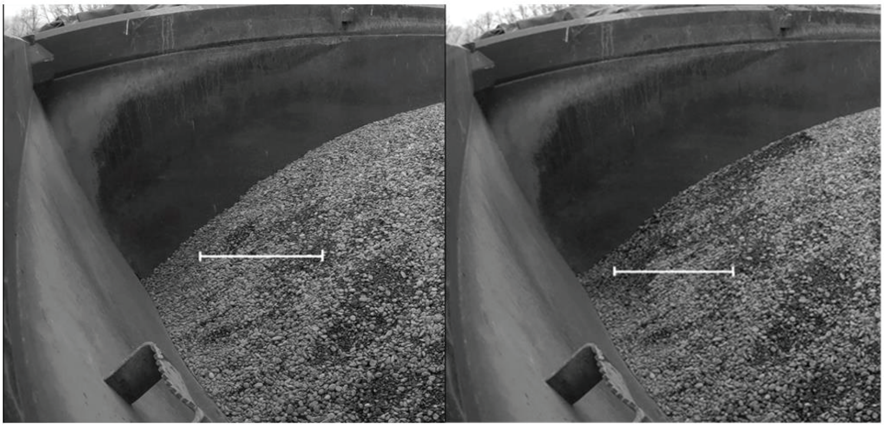

Fig. 3. Video exposures taken at 2s intervals.

During the gravel haulage experiment there was also a change in axle load. It changed markedly on axles 1, 5 and 6 by 2.4, 4.9 and 2.2%. At the same time, the maximum axle-weight error of the gravel truck did not exceed 1.3 per cent. If we compare the percent change of a load on each wheel before and after experiment we see, that at the road train with gravel the load at half of wheels has changed more than on 2 % and in some cases reached 9,4 % (the left wheel on 2-nd axle). The gravel train recorded a load change of more than 2% in 8 wheels and, as in the first case, the left wheel on the 2nd axle experienced a maximum change of 11.1%. Another proof of the load shifting in the semi-trailer was the video recording of the load in transit. Analysis of the video recordings showed that both crushed stone and gravel shifted in the semi-trailer when the vehicle was moving at high speed. Change of position of cargo particles in the semi-trailer is clearly seen in the frames (Figure 3) made by one of the video recordings at 2-s intervals.

4 Conclusion

On the basis of the experiment, we can conclude the following:

1. Bulk goods, in particular crushed stone and gravel, shift in the semi-trailer during transport, as evidenced by the results of the experiment to measure the level of the load in the semi-trailer and the video recording of the shifting moments.

2. Displacement of the bulk cargo in the semi-trailer leads to changes in the axle loads of the road train as evidenced by the experimental data obtained from the weight control carried out in accordance with the standard methodology used in determining whether the vehicle exceeds the permitted weight and the established axle load limits.

We can see from the results that when transporting loose goods, there will be shifts in relation to the sides of the semi-trailer even in the case of loose materials with high internal friction between the particles (crushed stones, gravel). In the case of bulk materials with low internal friction (wheat, oats, dry sand, etc.), large shifts must be expected at times of kinematic disturbances due to braking, turning of the vehicle, uneven road surface profile, etc. Therefore, in order to avoid axial overloads due to shifts of the bulk material, measures must be taken to reduce its mobility. For example, level the surface of the bulk cargo inside the semi-trailer and avoid sudden changes of driving modes during transport, or provide a load clamping device or install special diaphragms in the vehicle body similar to those for liquids transportation.

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