https://doi.org/10.26552/com.C.2016.2.76-82

COMMUNICATIONS

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COMPARISON OF ACCELERATION ACTING ON CARGO IN FRONT AND IN REAR PART OF SEMI-TRAILER DURING BRAKING WITH AND WITHOUT USING THE SYSTEMS ABS/EBS

This article deals with braking tests of semi-trailer truck in forward and rear driving direction. It compares the accelerations and angular velocities in the front and rear part of the semi-trailer and their influence on forces in lashing points when using front lashing. The paper also contains a comparison between forces reached in the lashing points at the rate of cargo weight between the braking tests of semi-trailer and similar braking tests of a van. The first part of the paper contains also possibilities of using tracking devices for detecting accelerations acting on cargo in semi-trailer during transport.

Keywords: *Braking tests, semi-trailer, forces in lashing points, front lashing, accelerations, tracking devices.*

1. Introduction and possibilities of using tracking devices for measurement of accelerations in cargo space

Wrong cargo securing causes a lot of damages on cargo and also traffic accidents in the worst cases. Transport of heavy cargo such as coils, metal rolls or rods is the most risky [1]. Damages on cargo are caused mostly by intensive braking, maneuvering and too high speed on penetrated carriageways. High accelerations occur not only in longitudinal axis owing to the braking (in forward and rear driving direction) but also in vertical axis, mainly when a vehicle rides fast on penetrated carriageways. This also has to be considered for cargo securing. These accelerations are different in front and rear part of semi-trailers and this is needed to take into account when proposing the cargo securing in semi-trailer trucks. Dynamic stress during transport and insufficient cargo securing may cause damages either on cargo or vehicle itself as a result of cargo movement, fall or collapse of pallet units [2]. In practice, if the cargo arrives damaged but no traffic accident happened, it is very difficult to prove, where and why the hidden damages on cargo occurred and who is responsible for them. At present, technical equipment such as cameras and tracking devices, which are often used in road transport, can help to improve an investigation of circumstances, where, how and why the damages caused by improper cargo securing happened. Simple analysis of GPS data about positions and speed is not very reliable for detection of intensive braking, mainly if device with lower frequency of coordinates acquiring is used (1 Hz is well for tracking and tracing, but not for reliable detection of braking parameters) or the data are from places with low quality of GPS signal such as mountain valleys and city industrial zones where roads are placed next to steel buildings [3]. Tracking devices equipped with accelerometers and other sensors (sensors of temperature, humidity, door contact, gyroscopes etc.) are also available today. Such devices can be used for complex recording of conditions acting on shipments during transport. Data from tracking devices are one of important inputs to logistic information systems [4]. Data from various sensors are usually not transmitted continuously during whole transport, but they are downloaded after the transport is finished. Analysis of these data provides better overview, whether the required conditions during transport were followed. Integrated accelerometers and gyroscopes allow an accurate detection of accelerations and angular speeds acting on cargo during whole transport. Moreover, some of such devices allow an automatic evaluation of accident situations with sending a message about them to dispatching center [5 and 6]. Such devices are suitable mainly for monitoring of transports of valuable and fragile cargo as well as transports of dangerous goods, because they are more expensive [5 and 7].

Devices intended for tracking and tracing of containers and other intermodal transport units have to be equipped also

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by satisfying battery capacity because such transports may last several weeks and no external source of energy is available usually [5 and 8]. Moreover, portable tracking devices are recommended also to improve the security. Using of two independent tracking devices in road vehicles, where one out of them should be placed in hidden place at the cargo space, is recommended because it brings a possibility of tracing of stolen vehicle also when GPS jammer is used in its truck cabin (it is common in cases of hijackings). Such portable tracking device should be placed in the rear part of semi-trailer [9]. If the device is also equipped with accelerometers, it can also be used for measuring the accelerations acting on cargo during the transport. Cargo in the rear part of semi-trailer is usually exposed to higher dynamic stress, which is also confirmed by our following research.

2. Measurements of accelerations during braking tests of semi-trailer

This paper deals with braking tests which were done with a semi-trailer truck and compares the accelerations reached in axes x, y and z in different parts of the semi-trailer. It also describes the influence of intensive braking on forces in front lashings used for cargo securing. A description of the semi-trailer truck used for these braking tests is given in Table 1.

The following equipment (incorporated to the Centre of Excellence for systems and services of intelligent transport at the University of Zilina [11]) was used for measuring of accelerations and angular velocities during the braking tests:

- XL meter™ Pro of University of Zilina[1]
- VDSU™ of University of Zilina[2], a sample rate of 200 Hz was used for evaluation of these tests. The placement of its two measuring units during the front and rear braking tests is shown in Fig. 1.

The forces in the two front lashings securing the two foremost coils of wire were measured in these braking tests by four load cells. The combined weight of the two coils was 4 040 kg. The distribution of the cargo is shown in Fig. 1. Different load set up was used for braking tests in forward direction and braking tests in the rear direction. Ten braking tests were done in forward driving direction from initial speed 35 - 40 km/h (except tests No. 9 and 10 where braking was initiated at speeds 31 and 27 km/h respectively). Out of these tests 1 to 4 were done with the systems ABS and EBS on and braking tests 5 to 10 with these systems off. Nine braking tests in rear driving direction from initial speed 11 - 12 km/h were also done, where the tests 1 to 4 were done with the systems ABS and EBS on and tests 5 to 9 with these systems off. The placement of the lashing points 1 to 4, in which the forces acting during braking were measured, is shown in Fig. 1. Lashing points No. 1 and 2 were behind the secured cargo and lashing points No. 3 and 4 were ahead of secured cargo, closer to the front end of semi-trailer.

Description of semi-trailer truck used for braking tests Table 1

Tractor	DAF FTXF H4EN3
Semi-trailer	Wielton NS3K
Curb weight of tractor	7 550 kg
Curb weight of semi-trailer	6 700 kg
Weight of cargo	12 100 kg
Total weight of semi-trailer truck	26 350 kg
Weight on axles in front braking tests	Tractor - front axle 6 550 kg, rear axle 9 040 kg Semi-trailer - tri-axle 3 x 3 590 kg
Weight on axles in rear braking tests	Tractor - front axle 6 330 kg, rear axle 7 540 kg Semi-trailer - tri-axle 3 x 4 160 kg
Cargo	6 coils of steel wire, each of them weighing about 2 000 kg
Floor in semi-trailer	Anti-skid plywood
Road surface used for braking tests	Dry asphalt with roughness on the road, placed askew to the driving direction before the braking place [10]

Source: Authors

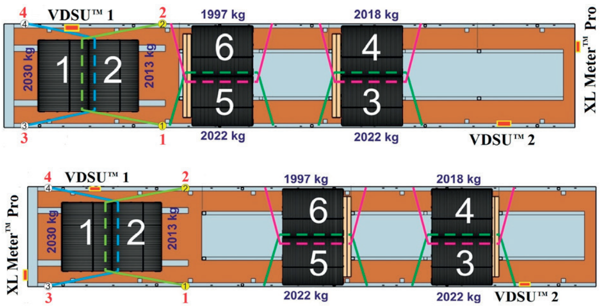

Fig. 1 Distribution of cargo, lashing points and measuring equipment during the forward braking tests (upper figure) and braking tests to the rear (lower figure). Source: Authors

3. Braking tests of semi-trailer truck in forward driving direction

The results of the braking tests in forward direction are given in Table 2 below. The data about the braking time, braking track, initial speed and mean fully developed deceleration (MFDD) were measured by the XL meter™ Pro device, except in tests No. 6 and 10, where the data from this device were not available, and therefore were replaced by calculated data from VDSU™ from

[1]http://www.inventure.hu/xl_meter_en
[2] http://www.inventure.hu/vdsu_en

Results of the braking tests in forward direction Table 2

Braking test	Braking time [s]	Initial speed [km/h]	Braking track [m]	MFDD [g][1]	Acc x in front part from VDSU™ [g][2]	Acc x in rear part from VDSU™ [g][3]	Acc x in rear part from XL meter™ Pro [g][3]	Forces SN1 + SN2 [daN][4]	Forces SN3 + SN4 [daN][4]
Braking tests with systems ABS and EBS on									
1	2.65	40.03	16.57	0.506	-0.503	-0.592	-0.604	970	308
2	2.54	41.01	15.53	0.537	-0.516	-0.599	-0.607	949	307
3	1.62	36.34	8.76	0.673	-0.712	-0.782	-0.795	1 525	702
4	1.78	35.34	9.81	0.652	-0.674	-0.752	-0.760	1 298	713
Braking tests with systems ABS and EBS off									
5	1.74	36.03	9.22	0.679	-0.726	-0.870	-0.803	1 491	616
6[5]	2.05	40.85	13.85	-	-0.689	-0.791	-0.689	1 356	540
7	1.98	40.91	11.89	0.659	-0.704	-0.839	-0.777	1 456	450
8	1.86	35.73	10.35	0.653	-0.620	-0.639	-0.729	1 184	498
9	1.56	31.45	7.64	0.702	-0.647	-0.765	-0.769	1 421	596
10[5]	1.485	27.17	7.3	-	-0.580	-0.690	-0.577	1 147	423

1 - MFDD was measured by the device XL meter™ Pro in the rear part of semi-trailer
2 – there are stated maximum accelerations reached during the braking in the front part of semi-trailer averaged in time of 80 ms
3 - there are stated maximum accelerations reached during the braking in the rear part of semi-trailer averaged in time of 80 ms
4 - there are stated maximum forces reached in particular braking tests
5 – data about the braking time, braking track and initial speed from the tests No. 6 and 10 are from the device VDSU™

Source: Authors

measuring unit 1 placed in the front part of semi-trailer. Accuracy of the data about the initial speed was verified by comparison with GPS data from device Garmin Virb Elite.

From the data in Table 2 above, it can be concluded that when the braking tests were done without using the systems ABS and EBS, the maximum reached values of braking deceleration (acting during 80 ms) were higher, especially in the rear part of semi-trailer. In two of these cases (No. 5 and 7) the deceleration reached (and according to the data from the VDSU™ even briefly exceeded) the value 0.8 g, which is the dimensioning acceleration specified in the standard EN 12 195-1:2010 [12] for calculation of cargo securing to prevent the movement in the forward direction. The accelerations acting on the cargo in the transverse axis y reached not more than 0.2 g in the rear part of semi-trailer. In the front part of the semi-trailer they were insignificant, about 0.05 g only. The diagram in Fig. 2 compares typical run of acceleration in longitudinal axis in the front and rear part of semi-trailer during braking.

The acceleration in the vertical axis z was oscillating during the braking and its values in the front part of semi-trailer did not exceed 0.2 g. In the rear part of semi-trailer this level was exceeded in braking tests 1, 3, 7 and 8, whereas the maximum measured value was 0.355 g in the braking test No. 8. However, higher vertical accelerations were measured before and after the braking. Before braking the semi-trailer truck drove across a roughness on the road, placed askew to the driving direction[3]. When the semi-trailer truck drove through it, the vertical acceleration ranged from -0.4 g to +0.4 g in the front part of semi-trailer and from -0.3 g to +0.3 g in the rear part of semi-trailer. Also after the vehicle stopped, vertical accelerations reaching about 0.6 g were generated in the rear part of semi-trailer. The plot of acceleration along the vertical axis before, during and after the braking is given in Fig. 3[4].

In Table 3, the average values are given for the maximum accelerations with a duration of at least 80 ms along axis x in the front and rear part of the semi-trailer, both for the braking tests with the systems ABS and EBS (tests No. 1 to 4) applied and without using these systems (No. 5 to 10).

[3] according to the requirements of the standard EN 12 642 for braking tests [10]
[4] differences up to +/- 0.1 g from stated peak values of accelerations in vertical axis were measured in particular braking tests

Average maximum reached values of acceleration in axis x acting for the time of 80 ms in the front and rear part of the semi-trailer Table 3

	Acc x in front part from VDSU™ [g]	Acc x in rear part from VDSU™ [g]	Acc x in rear part from XL meter™ Pro [g]
Braking tests with ABS, EBS	-0.601	-0.681	-0.692
Braking tests without ABS, EBS	-0.661	-0.766	-0.724

Source: Authors

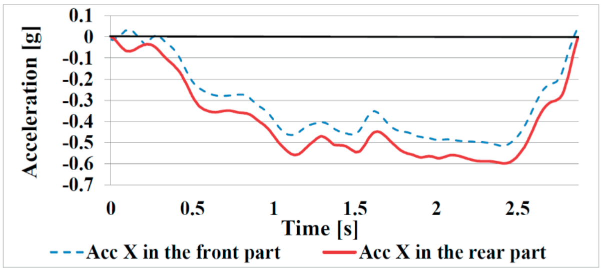

Fig. 2 Comparison of the acceleration in axis x in the front and rear part of the semi-trailer during braking in the braking test No. 2. Source: Authors

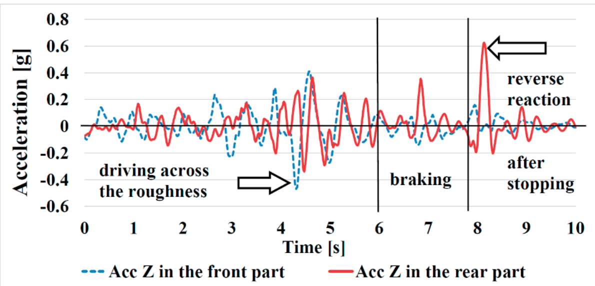

Fig. 3 Plot of the vertical acceleration (acc z) during the braking test No. 8. Source: Authors

The angular speed pitch (rotation around the transverse axis y) was also observed during the braking tests. High values of this angle speed were measured in the forward braking tests No. 5 to 8. The measured pitch ranged from 30 to 60 degrees/s (in the time of 80 ms) in the rear part of semi-trailer and acted downwards during the braking and upwards after the vehicle came to a stop. No intensive movement was observed in the front part of the semi-trailer. The pitch did not exceed 4°/s there. In the other forward braking tests the pitch values during braking and after stopping ranged from 2 to 5°/s both in front and rear part of the semi-trailer.

The lashing points No. 1 and 2 were during the braking stressed by increased lashing forces. The maximum combined lashing forces reached from 949 to 1 525 daN. The lashing force peaked simultaneously with the acceleration in the x-axis in the front part of semi-trailer, which points out the correlation between the accelerations reached during the braking and the forces in lashing points. The plot of forces was, after an initial period of increasing, relatively flat and the differences between maximum and average forces in lashings during the braking were not more than 15 %[5]. After the vehicle stopped there was a reverse reaction during which the forces in the lashing points 1 and 2 decreased almost to zero and the lashing points 3 and 4 became stressed by forces, the maximum sum of which reached 307 to 713 daN.

This means that lashing points 1 and 2 were stressed by the force equivalent to 25 - 38 % of cargo weight during braking and lashing points 3 and 4 were stressed by the force equivalent to 7 - 18 % of cargo weight during the reverse reaction after the vehicle came to a stop. For comparison, in similar braking tests which were done with a van, where the braking deceleration typically reached between 0.8 - 1.0 g, higher peak values of forces stressing the lashing points were observed. It means that the forces reached for a short time higher values than the average values of them during whole braking[6]. This occurred mainly when the slippery surface was used under the cargo and the braking was done from high initial speed. In braking tests performed with a van from initial speeds of 35 - 40 km/h (as is similar to the initial speed of these braking tests), the maximum peak values of forces reached about 78 % of cargo weight and the average values of forces were about 72 % of cargo weight when using a surface with friction coefficient 0.28 under the secured cargo. But when higher initial speed, from 60 to 90 km/h, was used in the braking tests with the van, peak values of forces in lashing points 1 and 2 equivalent to 114 % of cargo weight were observed and the average forces during braking were about 90 % of cargo weight. When a surface with higher friction coefficient (0.36) was used under the cargo, the peak values of the forces decreased significantly but their average values decreased only slightly. Plastic floor used in some of vans has lower friction coefficient (about 0.3) than wooden floor and anti-skid pads applied on it are not so efficient as when they are applied in contact with metal or wooden surface [13].

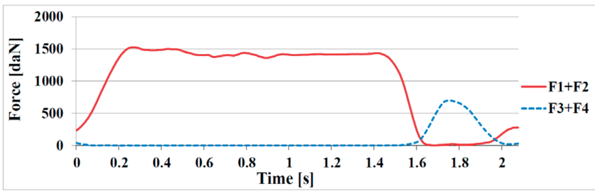

Fig. 4 Plot of forces in the lashing points 1+2 and 3+4 in the braking test No. 3. Source: Authors

[5] means: during settled phase when the forces acted, excepting increasing of forces at the beginning and decreasing of them at the end, see Fig. 4

[6] excepting main increase of forces at the beginning of braking and main decrease at the end of braking

A plot showing the forces in the lashing points during the braking and after stopping the semi-trailer truck is presented in Fig. 4 below.

4. Braking tests of semi-trailer truck in rear driving direction

Results of the nine braking tests in rear driving direction are presented in following Table 4.

In all braking tests in rear direction, accelerations exceeding 0.5 g for a duration of at least 80 ms were observed, both in the front and rear part of semi-trailer. The acceleration of 0.5 g is the level specified in the standard 12 195-1:2010 for calculation of cargo securing to prevent its movement in rear direction. We measured values of acceleration in the rear direction from 0.51 to 0.67 g in the front part of the semi-trailer and from 0.55 to 0.70 g in the rear part of the semi-trailer. Transverse accelerations did not reach high values and did not exceed 0.15 g in the front part of semi-trailer and 0.05 g in its rear part. Higher accelerations in comparison with the braking tests in front direction were measured in vertical axis z, in one case they exceeded 0.5 g. However, any higher vertical accelerations were not found out before braking and after the stopping as it happened in the braking tests in front direction. Higher values of vertical accelerations were recorded in the rear part of semi- trailer than in its front part. The angular pitch speed, meaning rotation around transverse axis y, reached 2 - 3°/s upward during the braking and 4 - 6°/s downward during the reverse reaction when the vehicle stopped in the rear part of semi-trailer. In the front part of semi-trailer the vertical movement was 1 - 3°/s during the braking and 2 - 5°/s during the reverse reaction after the stopping.

Table 5 presents average values of maximum accelerations acting in axes x and z with a duration of 80 ms in the front and

Results of the braking tests in rear driving direction

Table 4

Braking test	Braking time [s]	Initial speed [km/h]	Braking track [m]	MFDD [g][1]	Acc x in front part [g][2]	Acc x in rear part [g][3]	Acc y in front part [g][2]	Acc y in rear part [g][3]	Acc z in front part [g][2]	Acc z in rear part [g][3]
Braking tests with systems ABS and EBS on										
R1	0.78	11.85	1.25	-0.517	-0.592	-0.606	0.141	-0.049	0.421	0.556
R2	0.77	12.29	1.37	-0.533	-0.592	-0.596	0.149	-0.035	0.246	0.336
R3	0.8	11.65	1.32	-0.524	-0.572	-0.591	0.140	-0.023	0.291	0.352
R4	0.81	11.7	1.35	-0.490	-0.507	-0.553	0.144	-0.026	0.177	0.252
Braking tests with systems ABS and EBS off										
R5	0.85	11.65	1.54	-0.466	-0.570	-0.589	0.131	-0.020	0.300	0.371
R6	0.81	11.76	1.5	-0.488	-0.643	-0.678	0.106	-0.021	0.286	0.435
R7	0.99	11.43	1.89	-0.407	-0.587	-0.598	0.143	-0.021	0.272	0.404
R8	0.86	11.53	1.56	-0.441	-0.578	-0.592	0.121	-0.023	0.288	0.388
R9	-	-	-	-	-0.673	-0.697	0.128	-0.022	0.266	0.408

1- MFDD was evaluated by XL meter™ Pro placed in the front part of semi-trailer
2- there are stated maximum accelerations reached during the braking in the front part of semi-trailer averaged in time of 80 ms
3- there are stated maximum accelerations reached during the braking in the rear part of semi-trailer averaged in time of 80 ms

Source: Authors

Average maximum values of acceleration in axes x and z acting for the time of 80 ms in the front and rear part of the semi-trailer

Table 5

	MFDD [g]	acc x		acc z	
		in the front part [g]	in the rear part [g]	in the front part [g]	in the rear part [g]
Braking tests with ABS, EBS	-0.516	-0.566	-0.586	0.283	0.374
Braking tests without ABS, EBS	-0.451	-0.610	-0.631	0.282	0.401

Source: Authors

rear part of semi-trailer, both from braking tests with systems ABS and EBS on (braking tests 1 to 4) and with these systems off (braking tests 5 to 9). Although the MFDD values were lower in the braking tests without using the systems ABS and EBS, the maximum values of braking deceleration exceeded 0.5 g.

During the braking tests in rear direction the maximum combined forces in front lashings in lashing points 3 and 4 were from 600 to 1 100 daN, which is an equivalent of 15 - 28 % of cargo weight. These forces acted in the rear direction. During the reverse reaction after the stopping, lashing points 1 and 2 were stressed by combined forces of 500 - 900 daN in the forward direction, which is equivalent to 13 - 22 % of cargo weight. The highest forces in the lashings were reached during the first two braking tests. For comparison, in the similar braking tests with a van where a surface having friction coefficient 0.28 was used under the cargo the maximum combined forces in lashing points 3 and 4 reached an equivalent of 68% of cargo weight, and the average values (except the start of the force increase) were 61 % of cargo weight. Initial speed of braking in the van braking tests was about 15 km/h. When the surface with a friction coefficient 0.36 was used under the cargo, the average forces in lashing points 3 and 4 decreased to 38 % of cargo weight. Lashing points 1 and 2 were stressed by force equivalent to 23% of cargo weight when the surface with friction coefficient 0.28 was used and 14 % of cargo weight when the surface with friction coefficient 0.36 was used [13].

5. Conclusion

The main result of these braking tests is that higher accelerations in axes x and z are reached in the rear part of a semi-trailer than in the front part. Also the angle speed pitch (rotation around transverse axis y) reached higher values in the rear part in general, especially when the braking tests were done without using the systems ABS and EBS. However, in some cases of braking tests in front direction it also reached very high values. The highest forces in the lashing points, reaching about 38 % of cargo weight, were measured in the cases when the highest accelerations were reached in the front part of semi-trailer, where the monitored part of the cargo was placed. In two of the forward braking tests which were done without using the systems ABS and EBS, acceleration in axis x reaching or slightly exceeding 0.8 g, which is the dimensioning level specified in the standard EN 12195-1:2010 for calculation of cargo securing to prevent its movement in front direction, was observed. In the braking tests with the systems ABS and EBS applied this level was not exceeded. But the analogical level 0.5 g specified for cargo securing to prevent its movement in rear direction was exceeded in all 9 rear braking tests. The results of these braking tests confirm that higher accelerations and angle speeds acting on the cargo are needed to be considered in the rear part of a semi-trailer than in the front part for the securing of cargo. Tracking devices equipped with accelerometers can be used for recording of accelerations acting on cargo during the transport, which is useful to check, whether the required conditions during transport were followed and for investigation in case, if some damages on transported cargo occurred.

Acknowledgement

This paper is the result of the project implementation:

Centre of excellence for systems and services of intelligent transport, ITMS 26220120028 supported by the Research & Development Operational Programme funded by the ERDF.

Európska únia
Európsky fond regionálneho rozvoja

Operačný program
VÝSKUM a VÝVOJ

Agentúra
Ministerstva školstva, vedy, výskumu a športu SR
pre štrukturálne fondy EÚ

"We support research activities in Slovakia / This project is co-financed by the European Union"

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