Evaluation of Bulk Cargo Dynamics in the ACTS Intermodal Container

Procjena dinamike rasutih tereta u ACTS intermodalnom kontejneru

Peter Marienka
University of Zilina
Faculty of Operation and Economics
of Transport and Communications
Department of Road and Urban
Transport, Slovakia
E-mail: peter.marienka@fpedas.uniza.sk

Marcel Frančák
University of Zilina
Faculty of Operation and Economics
of Transport and Communications
Department of Road and Urban
Transport, Slovakia
E-mail: marcel.francak@fpedas.uniza.sk

Juraj Jagelčák
University of Zilina
Faculty of Operation and Economics
of Transport and Communications
Department of Road and Urban
Transport, Slovakia
E-mail: juraj.jagelcak@fpedas.uniza.sk

Summary

To ensure safety during transport within the intermodal chain, it is important to identify possible dynamic events that could affect the cargo. In the case of bulk cargo in an ACTS (Abroll-Container-Transport-System) container, the dynamics of the cargo and the vehicle vary during normal events such as braking, steering, evasive maneuver and the like. In this research, we used MEMS (Micro-Electro-Mechanical Systems) sensors to identify the parameters of acceleration at various points of container and to evaluate its impact on the cargo and vehicle. During the research, we also found out how the load of individual axles of the vehicle changed after performing normal dynamic events. One of the objectives was also to find out how parameters such as braking distance, braking time and mean fully developed deceleration (MFDD) change in the case of and empty and loaded ACTS container, as well as correlation analysis of values gathered from sensors placed on different parts of the container. The acquired knowledge can be used in the distribution and securing the cargo.

Sažetak

Kako bi se osigurala sigurnost tijekom transporta unutar intermodalnog lanca, važno je utvrditi moguće dinamičke događaje koji bi mogli utjecati na teret. U slučaju rasutih tereta u kontejneru ACTS (Abroll-Container-Transport-System), različita je dinamika tereta i vozila tijekom normalnih događaja, kao što su: kočenje, upravljanje, manevar izbjegavanja i slično. U ovom istraživanju koristili smo senzore MEMS (mikroelektromehanički sustavi) kako bismo identificirali parametre ubrzanja na različitim točkama kontejnera i procijenili njegov utjecaj na teret i vozilo. Tijekom istraživanja također smo otkrili kako se mijenjalo opterećenje pojedinih osovina vozila nakon izvođenja normalnih dinamičkih događaja. Jedan od ciljeva bio je otkriti kako se mijenjaju parametri, kao što su: put kočenja, vrijeme kočenja i prosječno puno usporenje (MFDD) u slučaju praznog i napunjenog ACTS kontejnera, kao i korelacijska analiza vrijednosti prikupljenih senzorima postavljenim na različitim dijelovima spremnika. Stečena znanja mogu se koristiti u raspodjeli i osiguranju tereta.

1. INTRODUCTION / *Uvod*

Safety is one of the key aspects of intermodal freight transport. The assessment of the correct distribution and securing of the cargo is based on the assumption of knowledge of the forces affecting the cargo, the intermodal load unit, and the vehicle. The cargo has different dynamics in normal or emergency situations, which can be measured and evaluated to identify the risk of damage to the cargo or vehicle. In the case of bulk cargo, this is more difficult to implement, as the cargo can only be secured in a very limited way. Transport of bulk cargo with high accelerations (decelerations) or large inclinations is quite different from the dynamics of common transport of cargo. To measure these dynamic events, it is necessary to use devices with accelerometers and gyroscopes. In order to determine the effect of these forces, a series of measurements must be taken with the ACTS container full of bulk cargo.

The importance of intermodal transport efficiency analysis is pointed out by Wiśnicki B. et al. [1]. Options of modeling of transport processes and transport mode choice are shown in the manuscript published by Gnap J. et al. [2],[3],[4]. The methodology of inland ports design as intermodal terminals in the Czech Republic was proposed in the article by Bínová and Jurkovič. [5]. Intermodal transport of goods can bring some specific shipments. One of them can be the transport of dangerous goods, which is described in Galierikova et al. article [6], as well as in Jagelcak J. et al. [7].

This article is also dedicated to axle load changes after dynamic events. There are many articles that deal with weight in intermodal transport, specifically article about VGM in intermodal transport by Jagelcak J. et al. [8] or about dynamic detection of the railway vehicles weight by Ližbetin J. et al. [10]. Nwokedi et al. assessed the shippers and ship owner's ships and charter type choice in the wet and dry bulk ship brokering market in the African region close to Nigeria [9].

Dynamic events described in this article were addressed in the past and many outputs are published, like simulation model of the dynamic behavior of refrigerated products in a ship's refrigerated container by Bupič M. et al. [12] or in applications of gyroscopic effect in transportation by Náhlík et al. [13]. The studies of vehicle dynamics lead to the safety of transport as described in Vlkovsky et al. articles [14], [27], [23] or in Skrucany et al. [17], [25], [28]. The aerodynamics, crosswind, safety systems, braking systems, cargo distribution must be taken into account as it is in articles by Gnap et al. [15],[21], Vrabel J. et al.[18], as well as Rybicka I. et al. [19] or Ondrus et al.[20] [24] [29]. These findings as well as information summarized in Rievaj V. et al. [22] [30] should be included in the research. The importance of using cameras to identify events in traffic is shown in Marienka P. et al. [16] and also in Tarkowski et al.[26]. As the article is also about the evaluation of dynamic events of transport for the purpose of cargo securing, it is necessary to take into account the research conducted in this area. Bańka et al. described lashing methods and mathematical basis of the process of selecting the number of lashings [11], while Stopka et al. determined the most suitable layout of space for the loading units' handling in the maritime port [40]. Kudlac et al. in their paper showed the identification of restricting criteria for a comprehensive assessment of logistics chains in intermodal transport [41]. Some of the findings used for the research were inspired by the article of Ližbetin and Stopka, in which authors proposed the case study of application of specific mathematical methods in the context of revitalization of defunct intermodal transport terminal [42].

2. METHODS AND DEVICES / *Metode i uređaji*

Measurements to determine the impact of the simulated transport events on the ACTS (Abroll-Container-Transport-System) intermodal container and the bulk cargo itself were performed within one day in a safe place so that the measurements do not endanger traffic safety or cause damage to the vehicle or cargo. Therefore, bulk cargo in the form of waste glass (bottles, sheet glass) was chosen, which was partially crushed. Dynamic events were measured using three sensors and two cameras on a MAN Abroller in combination with the ACTS container KAB-25, the parameters of which are given below.

2.1. Vehicle – MAN Abroller / *Vozilo MAN Abroller*

For handling the container and performing the measurements to evaluate the dynamics of the cargo in the ACTS container, a MAN Abroller vehicle was used. The vehicle is used to handle all ACTS containers up to a maximum length of 7 meters.

Table 1 Parameters of MAN TGS L.2007.46.004 Abroller
Tablica 1. Parametri MAN TGS L.2007.46.004 Abroller

Vehicle	N3G – Special lorry – BA hook lift for container transport
Configuration	6x4
Axles	3 axles
Engine power	309 kW
Gearbox	Manual 12
Empty weight	12 390 kg + ACTS container
Payload	13 610 kg
Total weight	26 000 kg
Axle load	8 000 kg / 9 500 kg / 9 500 kg
Axle wheelbases	4 500 mm / 1 400 mm
Maximum length of the container	7 meters

Source: Technical datasheet MAN

2.2. ACTS container – KAB-25 / *ACTS kontejner – KAB-25*

Bulk cargo in the form of waste glass was loaded into an intermodal ACTS container with the model designation KAB-25, which is commonly used for the transport of waste. However, such a container may be intended for the carriage of any bulk cargo in any part of the intermodal chain. The container is manufactured in accordance with DIN 30 722 standard.

Table 2 Parameters of ACTS container KAB-25
Tablica 2. Parametri ACTS kontejnera KAB-25

External dimensions	6 400 x 2 550 x 1 750mm (LxWxH)
Internal dimensions	6 000 x 2 480 x 1 500mm (LxWxH)
Gross mass	17 400 kg
Volume	25 cbm
Tare (label)	2 400 kg
Tare (weighed)	2 350 kg
Payload	15 000 kg
Hook height	1 570mm
Equipment	Hooks, ladder, back door

Source: Technical datasheet of container KAB-25

Figure 1 Vehicle with loaded container KAB-25
Slika 1. Vozilo s napunjenim kontejnerom KAB-25
Source: Authors

2.3. Sensors S1 and S2 / *Senzori S1 i S2*

MEMS (Micro-Electro-Mechanical Systems) sensors with a BOSCH accelerometer were used to measure the acceleration affecting the vehicles in various places of container. The accelerometer with a 14-bit LGA sensor can measure with different ranges. For the purposes of measurement the range was set to ±8 g with a sensitivity of 1 024 LSB/g. In addition to the accelerometer, the MEMS also integrates a 3-axis gyroscope, i.e. an angular velocity sensor with a flexible measuring range. Identical sensors S1 and S2 can, in addition to acceleration and angular velocity, also record the UNIX time track and GPS position. The sampling frequency of the accelerometer is at the level of 200 Hz.

2.4. Sensor S3 / *Senzor S3*

Sensors S1 and S2 were supplemented by a more accurate sensor S3, which was placed on the front of the loaded container. Sensor S3 is an acceleration sensor for evaluating the amount of acceleration (deceleration) of the service brake or the amount of acceleration. S3 is able to measure both positive and negative acceleration with a set range of ±2 g. Like S1 and S2, S3 can sample data at 200 Hz, every 5 ms. In addition to the measured data, the devices immediately evaluate the following indicators:
- v_0 – initial speed v km/h;
- s_0 – braking distance in meters;
- T_{br} – total braking time in seconds;
- MFDD – Mean Fully Developed Deceleration in m/s²;
where the braking time T_{br} is calculated by the difference

between the start braking time and the end braking time. The value of the initial vehicle speed v_0 is calculated by integrating the acceleration in the braking interval. The braking distance s_0 is calculated as the double integral of the acceleration in the braking interval. The S1 sensor is a verified device for measuring the dynamics acting on a vehicle in the automotive industry.

2.5. Cameras C1 and C2 / *Kamere C1 i C2*

To monitor what is happening to the vehicle and the cargo at certain accelerations, it was necessary to supplement the used sensors with a video recording. For these purposes, two cameras were chosen, which were placed in the same places as the sensors S1 and S2. Cameras C1 and C2 are identical, they are 1080p HD @ 23.98 FPS cameras with CMOS sensor.

3. DATA AND METHODOLOGY OF MEASUREMENTS / *Podatci i metodologija mjerenja*

Measurements with a loaded container were performed to identify the accelerations acting at different places of the ACTS container loaded with a bulk cargo in the form of waste glass. This load was chosen to eliminate the risk of damage to the cargo or the vehicle. For the purpose of these measurements, a MAN TGS 26.400 vehicle and ACTS container with the model designation KAB-25 were used, which are described in Chapter 2 of this article.

Three sensors were used to measure dynamic events. The S1 was placed on the front half of the ACTS container and was firmly fixed to it by magnets. Sensor S2 was fixed to the container on the top rim of the container, while S3 was placed in the front half of the container. Cameras C1 and C2 were also placed at the same places as S1 and S2 so that the video captures not only the current situation of the left side of the vehicle but also the bulk cargo itself.
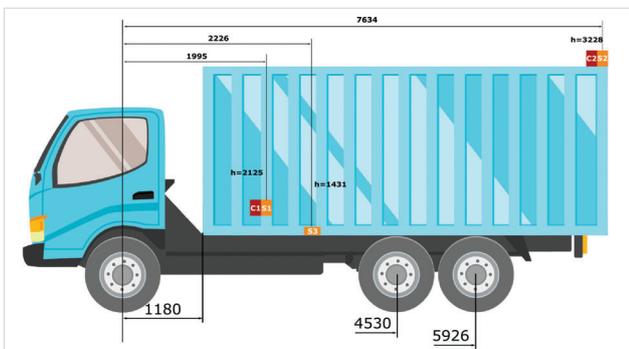

Figure 2 Scheme of the sensors and cameras locations during measurements
Slika 2. Shema položaja senzora i kamera tijekom mjerenja
Source: Authors

The scheme in Figure 2 describes the location of the sensors and cameras on the vehicle during measurements and their position, i.e. the distance from the front axle of the vehicle and their height (h). All dimensions are in millimeters.

To identify the dynamics acting on the vehicle, the container and the cargo, braking tests were chosen, while the driver was braking from an initial speed between 30 and 35 km/h. We made two series of these braking, while the total weight of the vehicle, as well as the weights of the front axle and the rear tandem axle were measured. During all measurements, selected indicators and accelerations given in multiples of g = 9.81 m/s² were monitored.

Figure 3 Views of C1 and C2.
Slika 3. Prikazi s C1 i C2
Source: Authors

4. DATA EVALUATION / *Procjena podataka*

From the cited monographs [30], [31], regulations [32], [33], [34], methodical instructions [35], [36] and standards [37], [38], it follows: the movement of a vehicle in traffic is uneven, depending on the circumstances it is necessary to accelerate, decelerate, change direction. From a safety point of view, one of the most important features is the efficiency of the brake system. In practice, the following requirements are imposed on the brakes:

- The braking system shall ensure a rapid and reliable stopping or deceleration of the vehicle or combination of vehicles at the speed, load condition, and gradient of the road which occurs during operation. The braking system must, therefore, be able to produce the required braking force on the circumference of all the wheels;
- The braking system of the individual wheels of the vehicle must be distributed among the individual wheels in such a way that braking does not impair the directional stability of the vehicle;
- The braking system must develop a braking effect even at an elevated temperature of the individual components of the braking system, which can be achieved e.g. during repeated intensive braking;
- The braking effect should be derived with the smallest possible time delay from the beginning of the action on the brake control.

When braking during real operation of the vehicle, as well as when evaluating the braking tests, it is necessary to realize that the course of braking deceleration is not constant, but changes over time. A simplified expression of the dependence of the magnitude of the braking deceleration in time can be seen in the graph in Fig. 4.
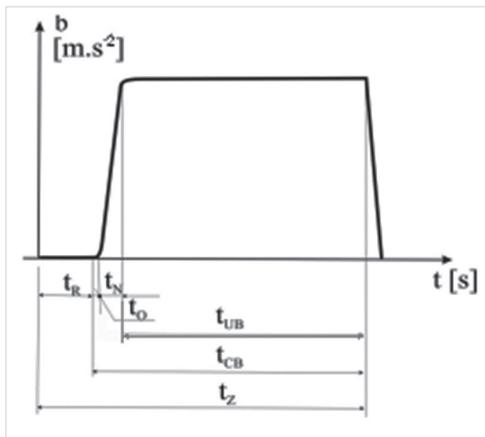
Figure 4 Theoretical course of braking
Slika 4. Teorijski tijek kočenja
Source: Rievaj V., Sulgan M., Hudak A., Jagelcak J.: The car and its dynamics.

The x-axis shows the time and the y-axis shows the amount of braking deceleration. We assume that the vehicle travels at a constant speed before braking, so the magnitude of the braking deceleration is 0 m/s^2. At time t_0, the driver notices an obstacle or registers a braking stimulus. The t_r reaction time follows. It is the time from the observation of an obstacle or stimulus to the moment when the driver decides to brake and touches the brake control mechanism. During this time, the vehicle is still moving at a constant speed, so the magnitude of the braking deceleration is still 0 m/s^2. This is followed by the delay time of the brakes, which lasts from the moment when the driver touches the brake control until the moment when the braking force begins to act. During this time, the mechanical clearance in the brake mechanism is defined. The delay time for the brakes is generally up to 0.15 s for air-assisted braking systems. When braking, we must also consider the time of onset of the braking effect. It is the time that elapses from the moment when the driver starts to act on the brake control element until the moment when the prescribed pressure is reached in the least favorably placed brake cylinder. According to UNECE Regulation 13, the time that elapses from the time the driver begins to act on the brake control until the moment when the pressure that reached the last brake cylinder is equal to 75% of the nominal pressure and it must not be greater than 0.6 s. During the ramp-up time, the braking deceleration increases from zero to full braking deceleration, i.e. the vehicle performs an unevenly decelerated movement. This is followed by the effective braking time here, during which the vehicle decelerated ideally evenly.

In practice, however, the vehicle decelerates unevenly due to the action of the ABS, as well as due to slight road irregularities, which is reflected in the value of braking deceleration during effective braking oscillating around a certain value – mean fully developed deceleration - MFDD.

The effectiveness of the braking system during the approval braking tests is also evaluated by MFDD. The MFDD can be determined from the stopping distance in relation to the initial speed of the vehicle by the formula:

$$d_m = \frac{v_b^2 - v_e^2}{25.92\,(s_e - s_b)}\ [m/s^2] \qquad (1)$$

where:
v_0 = initial vehicle speed in km/h
v_b = vehicle speed at 0,8 v_0 in km/h
v_e = vehicle speed at 0,1 v_0 in km/h
s_b = distance traveled by the vehicle between v_0 and v_b in metres
s_e = distance traveled by the vehicle between v_0 and v_e in metres.

The speed and distance shall be determined by instruments with and accuracy of ±1% of the prescribed test speed. The MFDD can be determined in other ways than by measuring speed and distance. In this case, d_m must be determined with and accuracy of ±3%.

The initial speed during the type-approval tests shall not be less than 98% of the speed for the prescribed test, which for vehicles of category N3 represents the value in the Type 0 test – basic cold brake test of 60 km/h in the engine disconnected test and 80% of the maximum design vehicle speed but not exceeding 90 km/h when tested with the engine connected. Also, during braking, the maximum permissible control force exerted by the driver on the brake control cannot be exceeded. For vehicles of category N3, this force shall not exceed 70 daN. The initial speed for Type 0 braking tests for selected vehicle categories are given in Table 3. We can also see the maximum braking distance and the minimum required MFDD for vehicle type-approval.

where:
v = prescribed test speed in km/h
s = braking distance in meters
d_m = mean fully developed deceleration in m/s^2
F = control force in daN
v_{max} = maximum vehicle speed in km/h.

Table 3 Initial speeds for Type 0 braking tests for selected vehicle categories
Tablica 3. Početna brzina za ispitivanja kočenja Tipa 0 za odabrane kategorije vozila

	Category	M2	M3	N1	N2	N3
	v	60 km/h	60 km/h	80 km/h	60 km/h	60 km/h
Type 0 test with engine disconnected	s	$0.15v + \dfrac{v^2}{130}$				
	d_m	5.0 m/s2				
	v = 0.80 v_{max} but not exceeding	100 km/h	90 km/h	120 km/h	100 km/h	90 km/h
Type 0 test with engine connected	s	$0.15v + \dfrac{v^2}{103.5}$				
	d_m	4.0 m/s^2				
	F	70				

Source: Regulation No 13 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of vehicles of categories M, N and O with regard to braking [2016/194].

In the Slovak Republic, it is obligatory to subject vehicles operated on-road to technical inspections at regular intervals depending on the category of vehicles, which are listed in §47 of the Decree of the Ministry of Transport and Construction of the Slovak Republic no. 137/2018 Coll., which lays down details on technical inspections. For vehicles of category N3 there is the obligation to pass the technical inspection within one year from its first registration and then periodically within one year.

During the technical inspection, the inspection of control items is divided into 10 groups, while for each group methodological instructions are issued indicating which components are to be checked and how. Brake systems belong to group 1. One of the control items of group 1 is to determine the magnitude of the braking effect. The braking effect can be measured by technical inspection stations in two ways – by driving test and by means of a roller brake tester. The braking performance test is generally performed on vehicles where it is not possible to perform the test on a cylinder brake test rig either in terms of their dimensions or in terms of their design. For the procedure for determining the effect of brakes on a roller brake tester, the Slovak Republic has issued Methodical instruction of the Ministry of Transport and Construction of the Slovak Republic no. 74/2018 for performing inspections of brake systems of vehicles of categories M1 with the maximum permissible weight over 3.5t, M2, M3, N2, N3, O3, and O4 on roller brake tester. For a vehicle of category N3 to be technically fit for braking performance, it is necessary to achieve the prescribed braking. The braking factor can be calculated according to the relation:

$$Z = 10.2 * \Sigma B_{vi}/m_c \qquad (2)$$

where:

ΣB_{vi} is the sum of the braking forces at the circumference of the axle wheels I given in N,

m_c is the maximum permissible gross vehicle mass stated in kg (the figure is given in F.1 of the registration certificate Part I and the registration certificate Part II).

According to the standard STN EN 12195-1:2010, in connection with the inertial forces considered for the design of load securing, the acceleration coefficients c_x, c_y and c_z are used. An acceleration coefficient determined, for example, of 0.8g in a given direction, means that it is necessary to secure 80% of the weight of the load in a given direction.

According to the standard prEN17321:2020, when dynamic acceleration tests are performed, minimum acceleration dwell time shall be 300 ms. The test value is the minimum acceleration recorded during the dwell time. When dynamic driving tests are performed, minimum acceleration dwell time shall be 1000 ms. While a duration of 80 ms the arithmetic average shall meet the required acceleration value. The arithmetic average of the required acceleration is allowed to fall below the required value by 0.05 g in case this value is applied over a period of one second.

Table 4 Prescribed braking values and their conversion to the actual deceleration achieved during braking
Tablica 4. Propisane vrijednosti kočenja i njihovo pretvaranje u stvarno usporavanje postignuto tijekom kočenja

	Vehicles of cat. N3 in first evidence from 1.1.2012	Vehicles of cat. N3 in first evidence in 1988 to 1.1.2012	Vehicles of cat. N3 in first evidence to 1988
braking factor [%]	50%	45%	43%
deceleration [g]	0.5	0.45	0.43
deceleration [m/s²]	4.9	4.4	4.2

Source: Methodical instruction of the Ministry of Transport and Construction of the Slovak Republic no. 48/2018, which lays down control items related to the braking device.

Table 5 Acceleration coefficients c_x, c_y and c_z for road, rail, and sea transport
Tablica 5. Koeficijenti ubrzanja c_x, c_y i c_z za cestovni, željeznički i pomorski promet

Road transport					
Securing in	Acceleration coefficients				
	Longitudinal (c_x)		Transversely (c_y)		Vertically down (c_z)
	forward	rear	Slide only	Turnover	
Longitudinal direction	0.8	0.5	-	-	1.0
Transverse direction	-	-	0.5	0.5/0.6	1.0
Rail transport					
Securing in	Acceleration coefficients				
	Longitudinal (c_x)		Transversely (c_y)	Minimum vertically down (c_z)	
	forward	rear		Slide only	Turnover
Longitudinal direction	1.0	0.6	-	1.0	1.0
Transverse direction	-	-	0.5	0.7	1.0
Sea transport					
Sea area	Securing in	Acceleration coefficients			
		Longitudinal (c_x)	Transversely (c_y)	Minimum vertically down (c_z)	
A	Longitudinal direction	0.3	-	0.5	
	Transverse direction	-	0.5	1.0	
B	Longitudinal direction	0.3	-	0.3	
	Transverse direction	-	0.7	1.0	
C	Longitudinal direction	0.4	-	0.2	
	Transverse direction	-	0.8	1.0	

Source: EN 12195-1:2010. Load restraining on road vehicles. Safety. Calculation of securing forces.
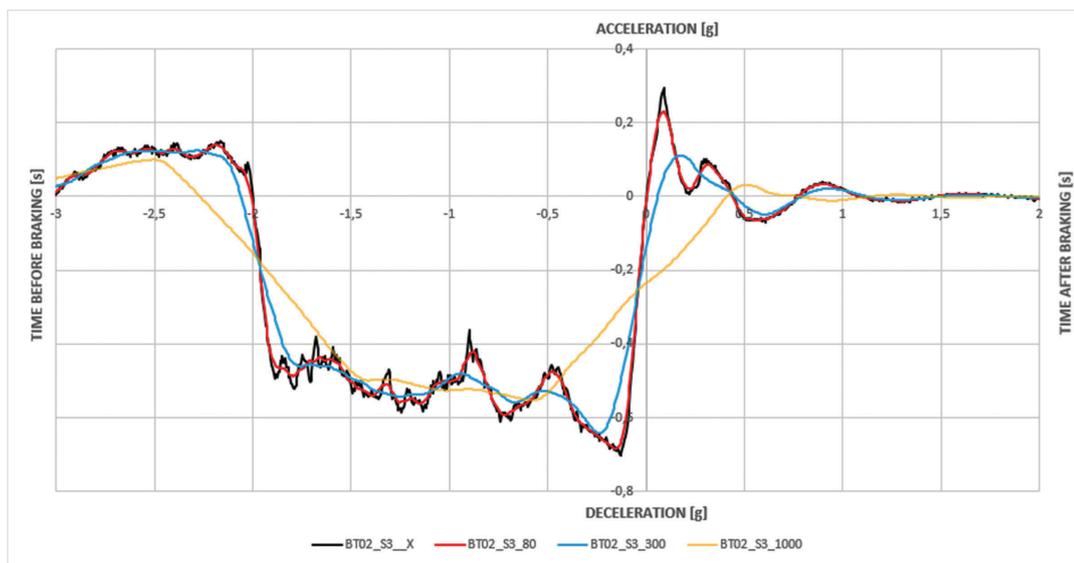
Figure 5 RAW data and application of moving averages 80 ms, 300 ms and 1000 ms.
Slika 5. RAW podatci i primjena pokretnih prosjeka 80 ms, 300 ms i 1000 ms

Source: Authors

For this reason, the raw data were filtered with a moving average of 80 ms, 300 ms and 1000 ms. The influence of these filters can be seen in Fig. 5. The maximum deceleration for the individual sensors is then shown in the tables.

4.1. Braking tests with empty container / *Ispitivanja kočenja s praznim kontejnerom*

The performed measurements can be divided into two main parts. In the first part, 8 braking tests were performed with an empty container using three sensors, while the measured maximum deceleration values for individual sensors with the application of three filters are shown in Table 6. The breaking courses with filters application are shown in Fig. 6.

4.2. Braking tests with loaded container / *Ispitivanja kočenja s natovarenim kontejnerom*

After performing the braking tests with the empty container, the container was loaded with waste glass weighing 9010 kg. With the loaded container, another 8 braking tests were performed. After four braking tests a short driving test was performed to monitor the movement of the bulk cargo in the container. The maximum values of decelerations for individual sensors with the application of three filters are shown in Table 7. The courses of measured braking decelerations using filters of 80 ms, 300 ms, and 1000 ms are shown in Figure 7.

Table 6 Braking tests with empty container (measurements BT01-08)
Tablica 6. Ispitivanja kočenja s praznim kontejnerom (mjere BT01-08)

| ID | s_0 [m] | v_0 [km/h] | T_{br} [s] | MFDD [m/s²] | Maximum deceleration [g] | | | | | | | | |
| | | | | | S1 | | | S2 | | | S3 | | |
					80ms	300ms	1000ms	80ms	300ms	1000ms	80ms	300ms	1000ms
BT01	10.43	35.65	2.02	5.16	-0.7114	-0.5787	-0.5362	-0.7353	-0.5844	-0.5414	-0.6364	-0.5749	-0.5362
BT02	10.29	35.64	1.97	5.18	-0.7033	-0.6483	-0.5443	-0.7068	-0.6549	-0.5479	-0.6849	-0.6426	-0.5535
BT03	9.50	34.15	1.87	5.60	-0.6824	-0.6077	-0.5764	-0.7012	-0.6129	-0.5774	-0.6588	-0.6051	-0.5792
BT04	9.40	34.17	1.90	5.30	-0.6478	-0.6064	-0.5539	-0.6593	-0.6134	-0.5436	-0.6417	-0.6119	-0.5514
BT05	9.12	32.40	1.90	5.09	-0.6729	-0.6292	-0.5245	-0.6817	-0.6817	-0.5358	-0.6617	-0.6274	-0.5365
BT06	8.56	32.22	1.78	5.46	-0.7330	-0.6905	-0.6031	-0.7414	-0.6527	-0.5811	-0.6814	-0.6451	-0.5776
BT07	9.33	33.45	1.87	5.41	-0.7217	-0.6041	-0.5713	-0.6969	-0.6093	-0.5754	-0.6752	-0.5922	-0.5701
BT08	9.95	35.21	1.98	5.17	-0.7189	-0.6930	-0.5813	-0.7156	-0.6863	-0.5755	-0.6971	-0.6658	-0.5666

Source: Authors
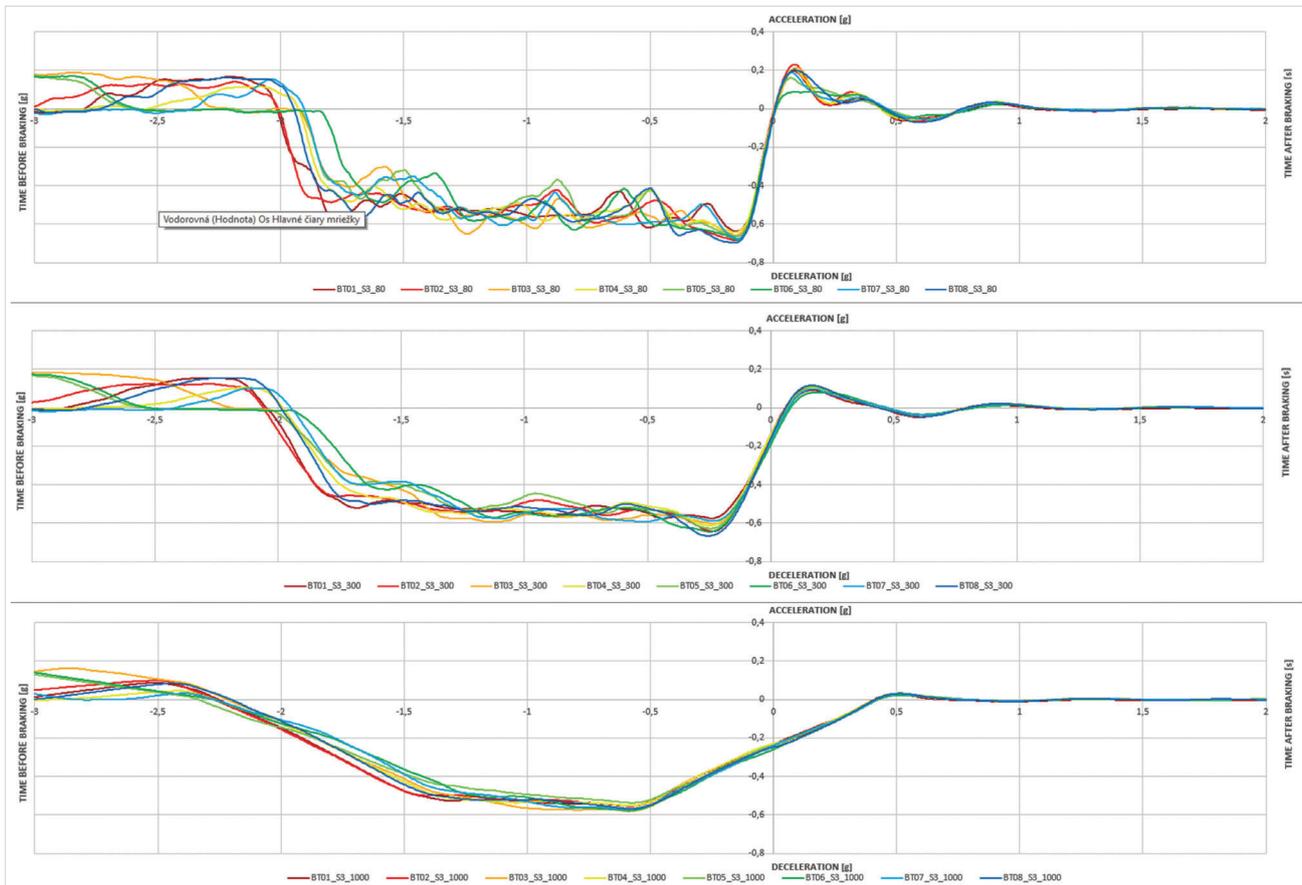
Figure 6 Braking tests BT01-08 measured with S3 and applied moving average filters
Slika 6. Ispitivanja kočenja BT01-08 izmjerena sa S3 i primijenjeni filtri s pomičnim prosjekom

Source: Authors

Table 7 Braking tests with loaded container (measurements BT09-16)
Tablica 7. Ispitivanja kočenja s natovarenim kontejnerom (mjere BT09-16)

ID	s_0 [m]	v_0 [km/h]	T_{br} [s]	MFDD [m/s²]	Maximum deceleration [g]								
					S1			S2			S3		
					80ms	300ms	1000ms	80ms	300ms	1000ms	80ms	300ms	1000ms
BT09	8.33	32.14	1.75	5.44	-0.6938	-0.6551	-0.5867	-0.7631	-0.6566	-0.5999	-0.6789	-0.6436	-0.5857
BT10	9.06	32.72	1.92	5.18	-0.6460	-0.5757	-0.5465	-0.7414	-0.6156	-0.5398	-0.5915	-0.5614	-0.5435
BT11	8.50	32.16	1.80	5.42	-0.6571	-0.5975	-0.5733	-0.6589	-0.5967	-0.5715	-0.6452	-0.5902	-0.5711
BT12	8.87	31.99	1.90	5.05	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*	-0.5677	-0.5129	-0.4900
BT13	8.70	31.85	1.91	5.00	-0.6172	-0.5452	-0.5240	-0.7618	-0.5833	-0.5387	-0.6042	-0.5507	-0.5248
BT14	9.21	32.34	1.93	5.13	-0.6413	-0.5919	-0.5365	-0.7742	-0.6188	-0.5393	-0.6032	-0.5663	-0.5236
BT15	10.3	35.60	2.03	5.04	-0.6728	-0.6167	-0.5489	-0.8498	-0.6725	-0.5597	-0.6351	-0.5903	-0.5369
BT16	7.10	29.11	1.72	5.17	-0.6407	-0.5884	-0.5286	-0.7368	-0.6168	-0.5292	-0.6205	-0.5940	-0.5217

Source: Authors
* N/A – measurement error, data not available
N/A – grješka mjerenja, podatci nisu dostupni

4.4 Comparison of braking distance, braking time and MFDD with empty and loaded container / *Usporedba puta kočenja, vremena kočenja i MFDD-a s praznim i napunjenim kontejnerom*

This section compares the mean fully developed deceleration (MFDD), braking distance, and braking time for both empty and loaded containers.

A comparison of braking distance, braking time and MFDD are shown in the graphs in Figure 8. In general, the braking distance reduced when the container was loaded and the MFDD was also reduced to some extent. According to Regulation No 13 of the Economic Commission for Europe of the United Nations (UN/ECE), the MFDD must be at least 5 m/s², which has been achieved in all cases.
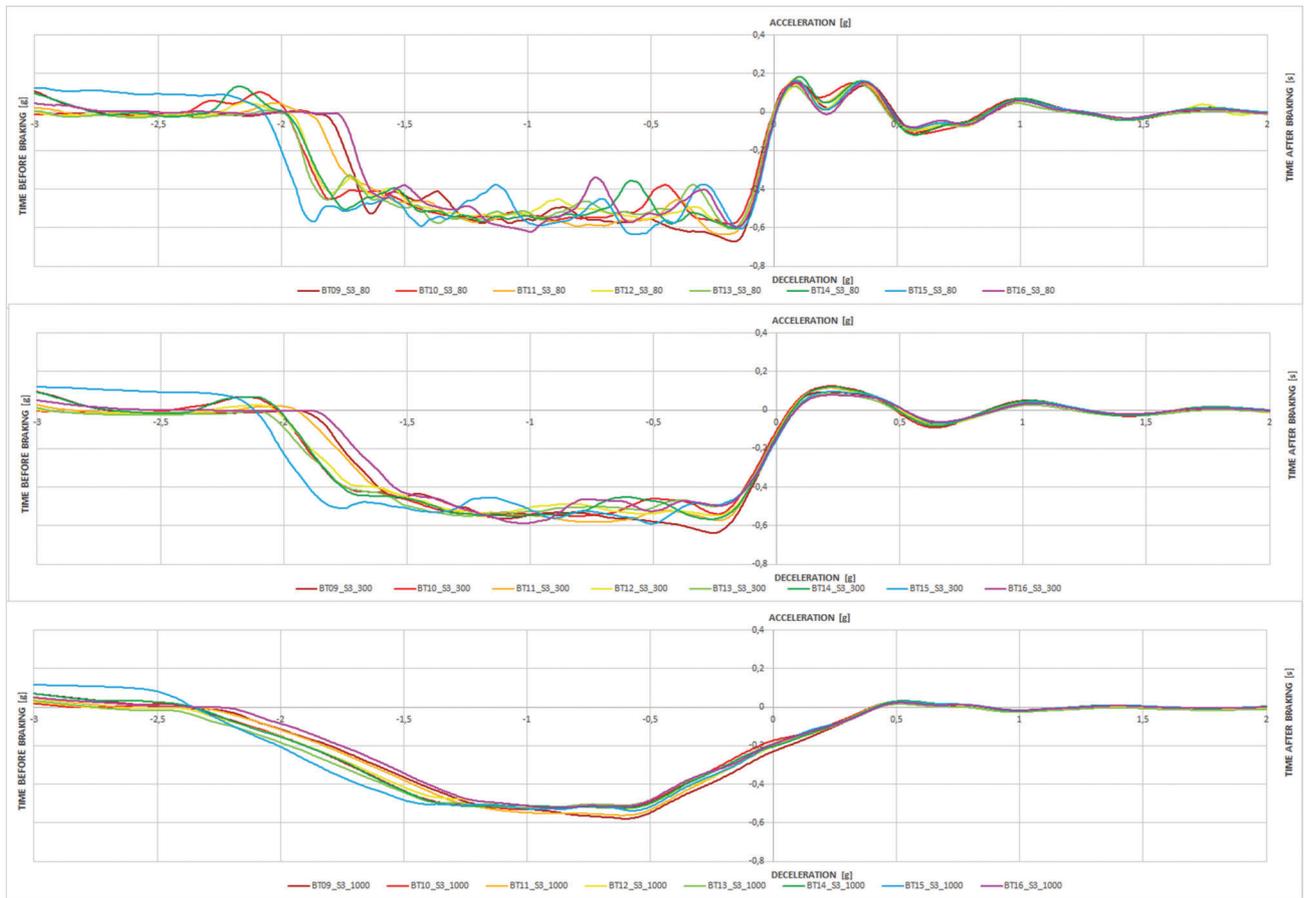
Figure 7 Braking tests BT01-08 measured with S3 and applied moving average filters
Slika 7. Ispitivanja kočenja BT01-08 izmjerena sa S3 i primijenjeni filtri s pomičnim prosjekom

Source: Authors

Table 8 Comparison of braking distance, braking time and MFDD
Tablica 8. Usporedba puta kočenja, vremena kočenja i MFDD-a

|	ID	s_0 [m]	v_0 [km/h]	T_{br} [s]	MFDD [m/s²]		ID	s_0 [m]	Diff [m]	v_0 [km/h]	Diff [km/h]	T_{br} [s]	Diff [s]	MFDD [m/s²]	Diff [m/s²]
Empty container	BT01	10.43	35.65	2.02	5.16	Loaded container	BT09	8.33	-2.10	32.14	-3.51	1.75	-0.27	5.44	+0.28
	BT02	10.29	35.64	1.97	5.18		BT10	9.06	+1.23	32.72	-2.92	1.92	-0.05	5.18	0
	BT03	9.50	34.15	1.87	5.60		BT11	8.50	-1.00	32.16	-1.99	1.80	-0.07	5.42	-0.18
	BT04	9.40	34.17	1.90	5.30		BT12	8.87	-0.53	31.99	-2.18	1.90	0	5.05	-0.25
	BT05	9.12	32.40	1.90	5.09		BT13	8.70	-0.42	31.85	-0.55	1.91	+0.01	5.00	-0.09
	BT06	8.56	32.22	1.78	5.46		BT14	9.21	+0.65	32.34	+0.12	1.93	+0.15	5.13	-0.33
	BT07	9.33	33.45	1.87	5.41		BT15	10.30	+0.97	35.60	+2.15	2.03	+0.16	5.04	-0.37
	BT08	9.95	35.21	1.98	5.17		BT16	7.10	-2.85	29.11	-6.1	1.72	-0.26	5.17	0

Source: Authors
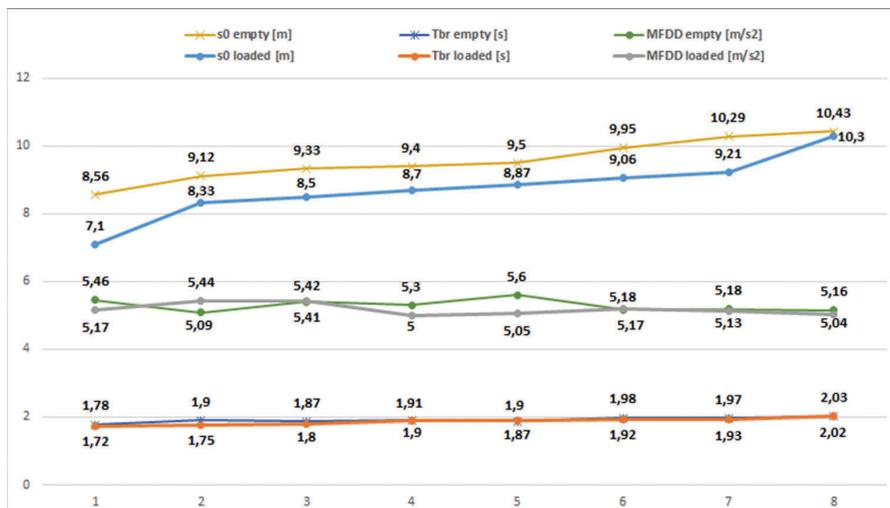
Figure 8 The differences of MFDD, braking distance and braking time with empty and loaded container
Slika 8. Razlike MFDD-a, puta kočenja i vremena kočenja s praznim i napunjenim kontejnerom

Source: Authors

4.5. Comparison of decelerations at different places of the container / *Usporedba usporenja na različitim točkama kontejnera*

The location of the sensors S1 and S2 have been designed so that it is possible to monitor the different dynamics acting on the vehicle at the front in the lower part of the container and the rear in the upper part of the container and to compare these values with each other. This chapter of the article will, therefore, focus on the comparison of S1 and S2 and the achieved maximum decelerations with the application of filters in the form of a moving average of 80 ms, 300 ms, and 1000 ms period.

When analyzing the braking courses with the application of the 80 ms filter, it is possible to see that in the case of an empty container, large differences in the deceleration curves are not visible. In the case of a loaded container, the difference is visible, especially in the length of the braking as in the resulting recoil after braking. The curves of S2 are shown in green colors, while the S1 curves are displayed in orange colors.

A comparison of the maximum acceleration values with the application of the individual filters is shown in Fig. 12.

Table 9 Comparison of maximum decelerations achieved by S1 and S2
Tablica 9. Usporedba maksimalnih usporavanja postignutih sa S1 i S2

| ID	Maximum deceleration [g]						ID	Maximum deceleration [g]					
	S1			S2				S1			S2		
	80ms	300ms	1000ms	80ms	300ms	1000ms		80ms	300ms	1000ms	80ms	300ms	1000ms
BT01	-0.7114	-0.5787	-0.5362	-0.7353	-0.5844	-0.5414	BT09	-0.6938	-0.6551	-0.5867	-0.7631	-0.6566	-0.5999
BT02	-0.7033	-0.6483	-0.5443	-0.7068	-0.6549	-0.5479	BT10	-0.6460	-0.5757	-0.5465	-0.7414	-0.6156	-0.5398
BT03	-0.6824	-0.6077	-0.5764	-0.7012	-0.6129	-0.5774	BT11	-0.6571	-0.5975	-0.5733	-0.6589	-0.5967	-0.5715
BT04	-0.6478	-0.6064	-0.5539	-0.6593	-0.6134	-0.5436	BT12	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
BT05	-0.6729	-0.6292	-0.5245	-0.6817	-0.6817	-0.5358	BT13	-0.6172	-0.5452	-0.5240	-0.7618	-0.5833	-0.5387
BT06	-0.7330	-0.6905	-0.6031	-0.7414	-0.6527	-0.5811	BT14	-0.6413	-0.5919	-0.5365	-0.7742	-0.6188	-0.5393
BT07	-0.7217	-0.6041	-0.5713	-0.6969	-0.6093	-0.5754	BT15	-0.6728	-0.6167	-0.5489	-0.8498	-0.6725	-0.5597
BT08	-0.7189	-0.6930	-0.5813	-0.7156	-0.6863	-0.5755	BT16	-0.6407	-0.5884	-0.5286	-0.7368	-0.6168	-0.5292

Source: Authors
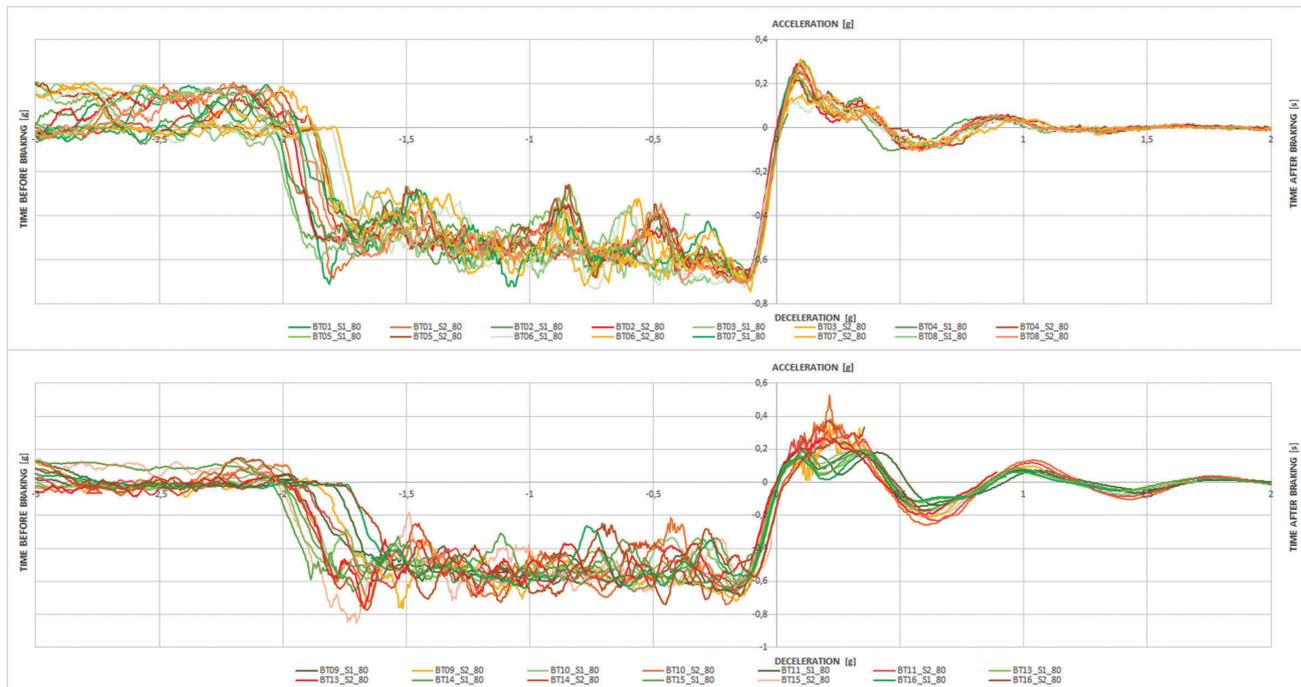
Figure 9 Comparison of S1 and S2 with 80 ms filter application
Slika 9. Usporedba S1 i S2 s primjenom filtra od 80 ms
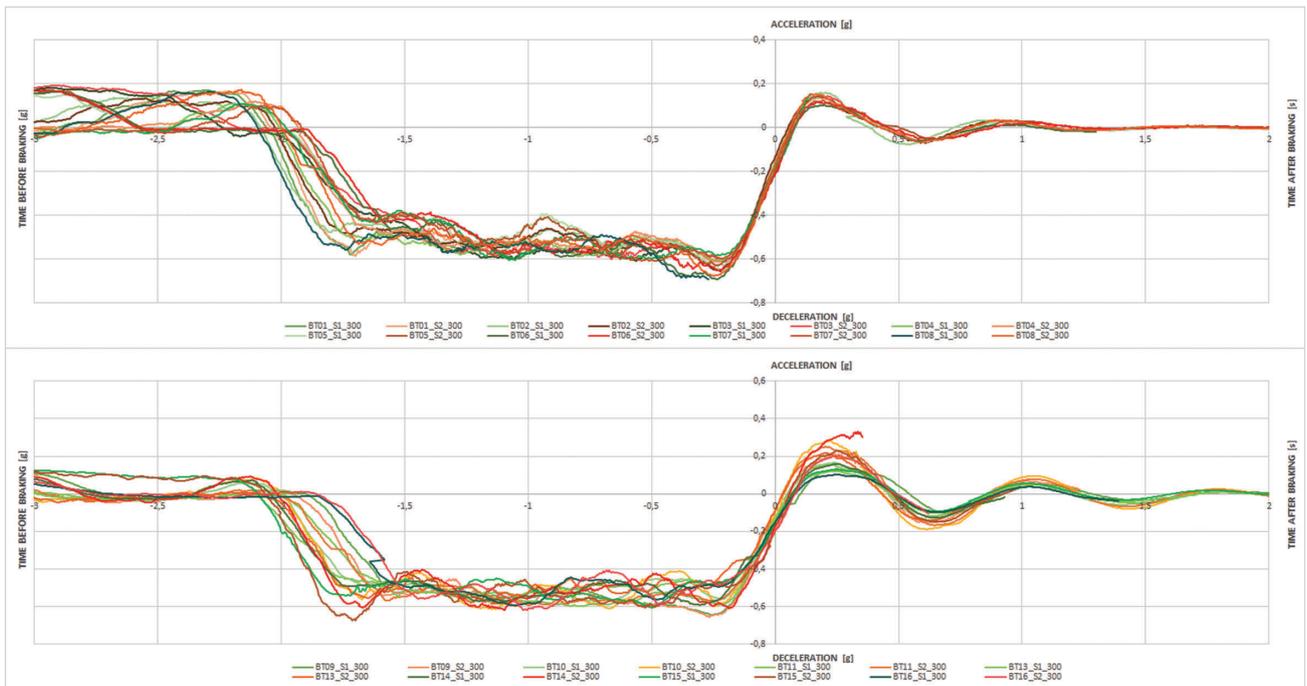
Source: Authors

Figure 10 Comparison of S1 and S2 with 300 ms filter application.
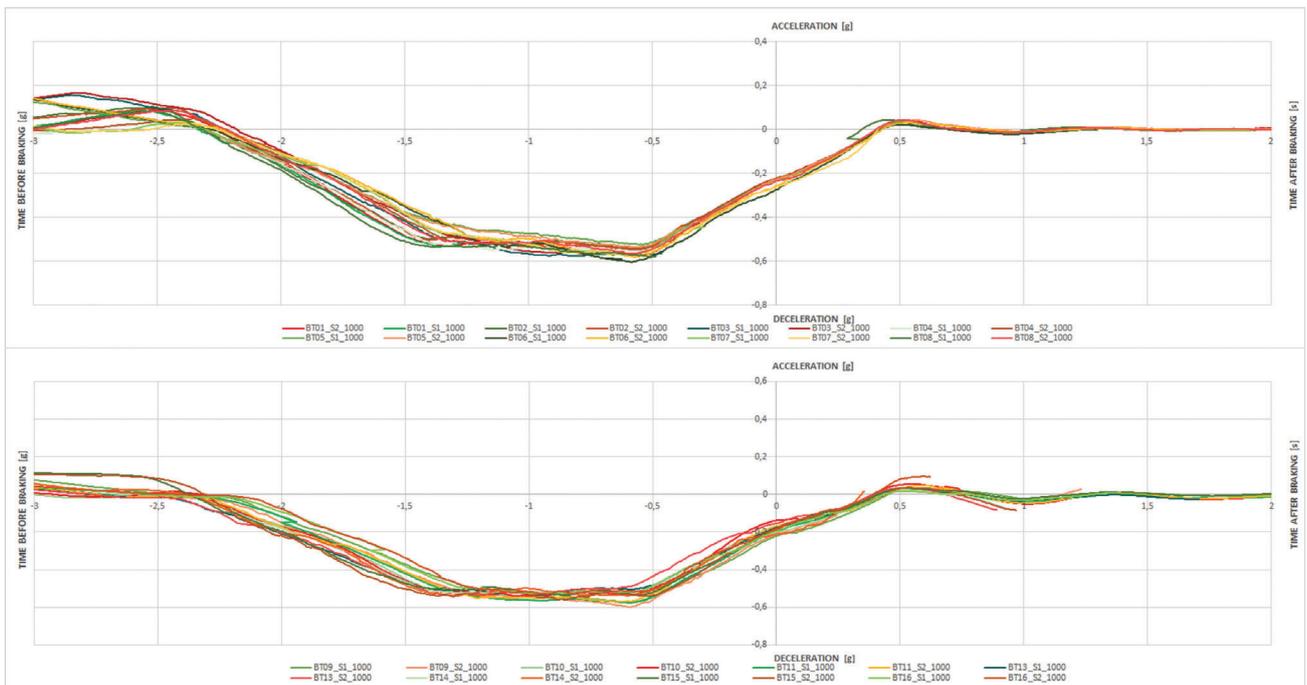*Slika 10. Usporedba S1 i S2 s primjenom filtra od 300 ms*

Source: Authors

Figure 11 Comparison of S1 and S2 with 1000 ms filter application
Slika 11. Usporedba S1 i S2 s primjenom filtra od 1000 ms
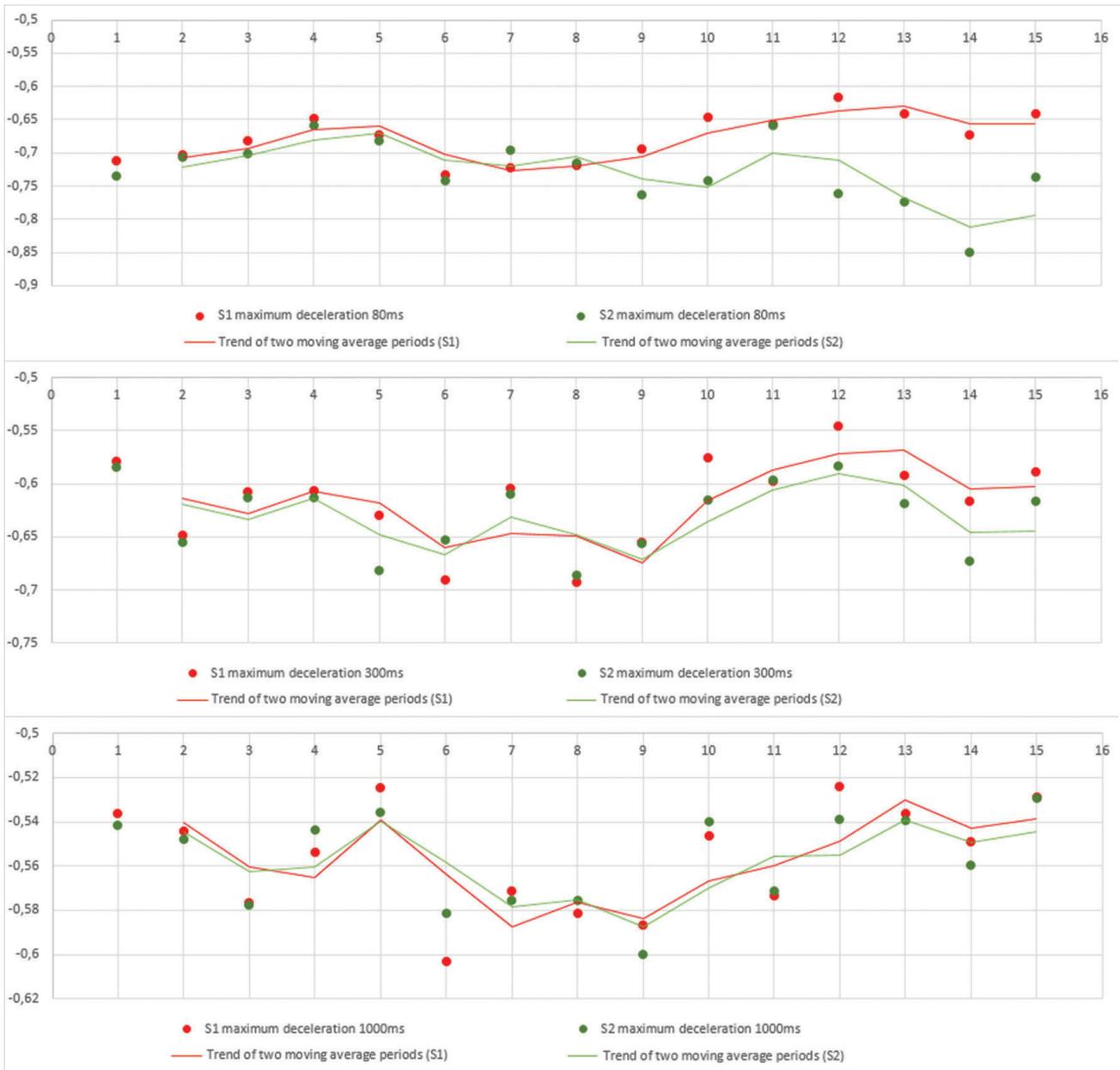
Source: Authors

Figure 12 Comparison of measured maximum deceleration of S1 and S2 with application of filters.
Slika 12. Usporedba izmjerenog maksimalnog usporavanja S1 i S2 s primjenom filtra

Source: Authors

From Fig. 12 we can observe the differences in the maximum measured decelerations of sensors S1 and S2. The data from sensors depend on the application of a particular filter and also on whether the vehicle is empty or loaded. While the container was empty and 80 ms filter was applied, the maximum measured deceleration values measured by both sensors are similar, after loading the container with glass, we observe (except the measurement BT11) differences between the maximum deceleration of S1 and S2 at 0.07 to 0.18g. In the case of an empty container and 300 ms filter, there was a gap between the maximum deceleration measured by S1 and S2 in the fifth and sixth measurements. After loading the container, we can see comparable values from individual sensors at BT09 and BT11, other measurements show higher maximum deceleration measured by S2. When a 1000 ms filter is applied, the values measured by both sensors are comparable, the largest difference occurred in measurement BT06 with an

empty container, when the maximum deceleration from the two sensors differed by approximately 0.02 g.

It was also examined whether there was a correlation between the measured maximum decelerations. The correlation coefficient according to [39] was used:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) * (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 * (y_i - \bar{y})^2}}$$

(3)

The correlation coefficient gives a statistical linear relationship between the values of the variables X and Y. The correlation between individual sensors and filters was determined separately for braking with an empty container, separately for a loaded container and subsequently between decelerations achieved by one sensor, where we compared the correlation between BT01-BT08 to BT09-BT16.

Table 10 Correlation coefficients
Tablica 10. Koeficijenti korelacije

		r value	corr.			r value	corr.			r value	corr.
EMPTY	S1S2_80ms	0.8579	SDD	LOADED	S1S2_80ms	0.1976	WDD	EMPTY vs LOADED	S1ES1L_80ms	0.3602	WDD
	S1S3_80ms	0.5917	MDD		S1S3_80ms	0.8400	SDD		S2ES2L_80ms	0.0221	LI
	S2S3_80ms	0.2975	WDD		S2S3_80ms	-0.0556	LI		S3ES3L_80ms	-0.2352	WID
	S1S2_300ms	0.8130	SDD		S1S2_300ms	0.8061	SDD		S1ES1L_300ms	-0.5182	MID
	S1S3_300ms	0.9438	SDD		S1S3_300ms	0.9244	SDD		S2ES2L_300ms	-0.6517	MID
	S2S3_300ms	0.9012	SDD		S2S3_300ms	0.6296	MDD		S3ES3L_300ms	-0.3816	WID
	S1S2_1000ms	0.9370	SDD		S1S2_1000ms	0.9444	SDD		S1ES1L_1000ms	-0.1409	WID
	S1S3_1000ms	0.9230	SDD		S1S3_1000ms	0.9784	SDD		S2ES2L_1000ms	-0.2114	WID
	S2S3_1000ms	0.9550	SDD		S2S3_1000ms	0.9315	SDD		S3ES3L_1000ms	-0.0533	LI

Source: Authors

If the correlation coefficient reaches a value from -1 to -0.7 or +1 to +0.7, we speak of strong indirect/direct dependence (SID/SDD). If the correlation coefficient reaches a value from -0.7 to -0.4 or +0.7 to +0.4, it is a middle indirect/direct dependence (MID/MDD). If the correlation coefficient is at the level from -0.4 to -0.1 or +0.4 to +0.1, it is a weak indirect/direct dependence (WID/WDD). A correlation coefficient in the range -0.1 to +0.1 indicates linear independence.

When looking at the correlation coefficients from the maximum deceleration in the case of an empty container, it is always a strong direct dependence (SDD), except for the cases S1S3 and S2S3 with the application of the 80 ms filter. In the

case of a loaded container, in most cases it is also a strong direct dependence (SDD), except for the cases S1S2 and S2S3 with a S2S3 with a 300 ms filter, which is MDD. In the case of the correlation coefficients, where the empty and loaded containers were compared, it is mainly a weak and middle indirect dependence.

4.6. Axle load changes / *Promjene osovinskog opterećenja*

Before the measurements, the load of the axles of the vehicle was determined. These weights were also measured after the first series of measurements, i.e. after tests with an empty container, after four braking tests with a loaded container, after a short driving test and after all measurements had been completed. The weighbridge was used to determine the front axle load, the total weight of the vehicle, and the load of the rear tandem axle. These values are processed in the following table and graph.

Primary load changes on the front axle and rear tandem axle were monitored after tests. Due to braking tests, the bulk cargo was naturally pushed forward in the container, which was reflected in the change of load on the front axle – after four braking tests with cargo, the load on the front axle increased by 280 kg (+3.6%). Since the subsequent driving test was performed with ascent and descent and multiple intensive braking, the load has leveled. After all tests, it was found that the load on the front axle increased by 400 kg (+5.18%), while the load on the rear tandem axle decreased by 360 kg (-2.23%). The inaccuracy and deviations arising from the measurements and the weighbridge shall also be taken into account.
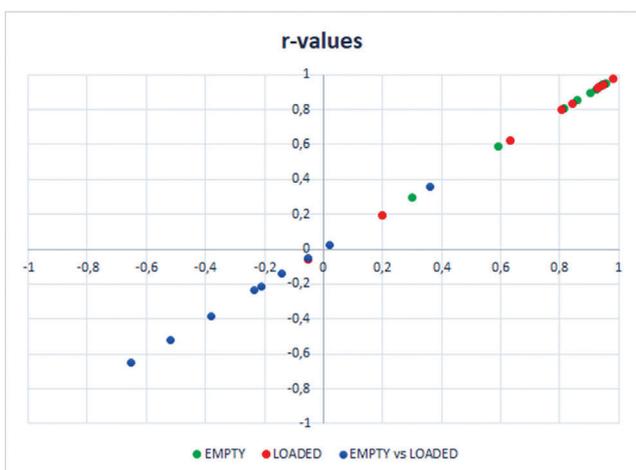

Figure 13 Correlation coefficients (r-values)
Slika 13. Koeficijenti korelacije (r-vrijednosti)
Source: Authors

Table 11 Weights after measurements
Tablica 11. Težine nakon mjerenja

| Cargo	Container	Measured	Front axle [kg]	Diff [kg]	Diff [%]	Total weight [kg]	Diff [kg]	Diff [%]	Rear tandem axle [kg]	Diff [kg]	Diff [%]
Without	Without	Before tests	6 200	-	-	12 620	-	-	6 350	-	-
Without		Before tests	6 510	+310	+5	14 970	+2 350	+18.6	8 450	+2 100	+33.1
Waste glass	KAB25	Before tests	7 720	+1 210	+18.6	23 980	+9 010	+60.2	16 160	+7 710	+91.2
		After 4 braking tests	8 000	+280	+3.6	23 980	-	-	15 850	-310	-1.9
		After driving test	8 040	+40	+0.5	23 980	-	-	15 940	+90	+0.6
		After 8 braking tests	8 120	+80	+1	23 980	-	-	15 800	-140	-0.9

Source: Authors
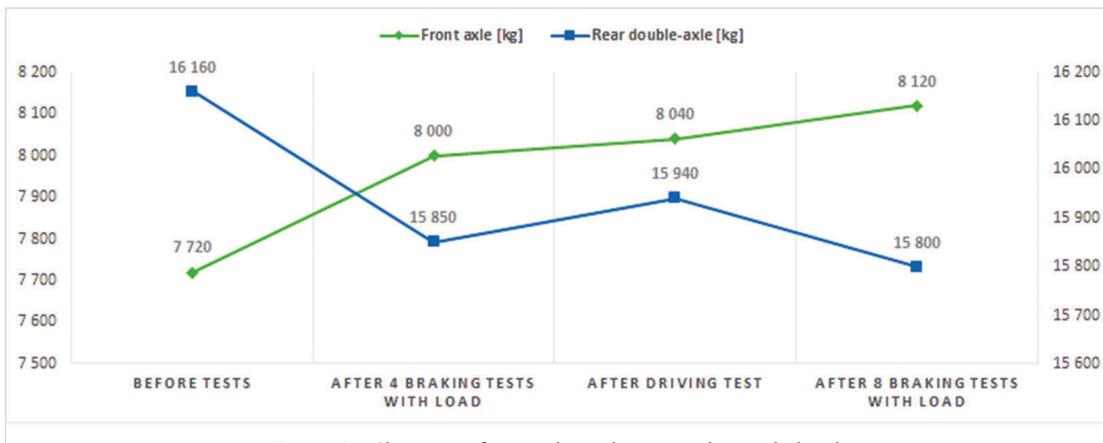
Figure 14 Change in front axle and rear tandem axle load
Slika 14. Promjena opterećenja prednje i stražnje tandemske osovine

Source: Authors

5. CONCLUSION / *Zaključak*

In this article, we dealt with the evaluation of the dynamics of bulk cargo in the intermodal container ACTS. We performed several measurements to identify the acceleration that affects the bulk cargo in the container we chose. The measurements were performed with the empty container, then with the loaded container. To measure acceleration, we used two sensors located in different parts of the container, and two cameras to record the movement of the vehicle and the movement of the cargo in the container. The measured acceleration values due to the nature of the sensors used cannot be evaluated directly, so it was necessary to make adjustments by applying a suitable filter.

Due to the requirements of the prEN 17321:2020 standard, we used a moving average of 80 ms, 300 ms, and 1000 ms. We evaluated the filtered data with the help of software in tabular and graphical form. From the results we can see that the braking distance, braking time, and MFDD of the vehicle with empty and loaded container do not change significantly, while taking into account the fact that the initial speed of the vehicle before braking differs slightly in both empty and loaded container tests. However, the difference is noticeable in the curves of braking, when the vehicle is stopped, and when the recoil occurs. Its duration is shorter when the container is empty than the case when the container is loaded. This deviation is most visible with the 80 ms filter. This phenomenon can be caused by a change in the height of the vehicle's center of gravity due to the bulk cargo, which also affects the change in the front and read tandem axle load during braking and thus the vehicle's suspensions tend to return. The difference is also observed at the maximum deceleration values achieved by S1 and S2 when the container was loaded. This difference is again most pronounced with the 80 ms filter application, with the 300 ms and 1000 ms filters are comparable.

We assume that during braking there was a suspension of the front axle and subsequent impact on the suspension stops, which significantly affected the angular speed of tilting the vehicle forward. S2 was placed at a higher height, where changes in the angular speed of the vehicle are more pronounced during braking. After tests, the front axle load increased by 400 kg, which exceeded its technical permissible maximum weight by 120 kg. The loading organization should also take into account the fact that the dynamic changes with bulk cargo may occur when the vehicle is in operation and these shipments should be modeled in such a way that the maximum axle weights are not exceeded.

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