

# Simulation Aspects of the Complex Mechanical System "Vehicle - Cargo" Exposed to Various Mechanical Loads

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**Abstract:** Inadequate cargo securing can lead to personal injuries, traffic fatalities, and property damage. In the context of research into new simulation methods, it became necessary to investigate relationships through simulations, such as the change in cargo slippage as a function of truck wheel suspension spring stiffness and braking deceleration. In the first part of the study, a simulation model of a vehicle-cargo mechanical system was compiled, consisting of two-axle N2-category truck and an intermediate bulk container (IBC). Subsequently, a series of braking simulations was performed using the truck-cargo simulation model. Based on the evaluation of the simulation results, the influence of wheel suspension stiffness and braking deceleration on the forward motion of inadequately secured cargo on the loading platform during braking was analyzed.

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## 1. INTRODUCTION

Incomplete or the complete lack of cargo securing can cause the cargo moving or slipping on the loading surface; in severe cases, the cargo may even fall off the loading surface. Such events can result in personal injury, fatalities, and material damage.

A deeper understanding of the relationship between cargo motion and the development of novel simulation procedures for cargo securing can indirectly contribute to improved road traffic safety (Ignác & Lakatos, 2022) by supporting the introduction of effective measures.

In preparation for the validation of the recently developed new simulation method (Ignacz et al., 2025) for solving cargo securing problems (MBS lashing strap model), it is important to clarify certain physical relationships, such as the effect of braking deceleration and vehicle suspension stiffness on the forward motion of the cargo during braking maneuver.

The aim of this study is therefore to analyze the effect of truck wheel suspension spring stiffness and braking deceleration on the motion of unsecured cargo placed on the truck's loading platform during braking maneuver.

## 2. MATERIALS AND METHODS

The simulations in this study were performed using PC-Crash software version 15.1. This software is widely used, among other things, for road traffic accident simulation reconstruction and is considered one of the leading software in this field (Dr. Steffan Datentechnik Ges.m.b.H., 2025). In addition, PC-Crash can also be used to develop new accident simulation methods. The software has been systematically validated

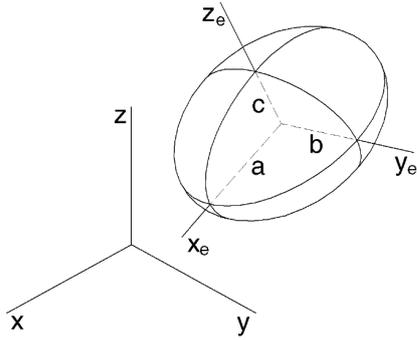
through real-world experiments for more than two decades, and the results have been published regularly (Dr. Steffan Datentechnik, 2025; Dr. Steffan Datentechnik Ges.m.b.H., 2025; Kurzke & Weyde, 2017; Moser & Steffan, 2008, 2015; Rose & Carter, 2018; Urban et al., 2017).

The simulations were performed using a kinetic simulation method, taking into account the forces acting on the vehicle and the load, as well as dynamic effects important for the present study, such as suspension characteristics (Dr. Steffan Datentechnik, 2025) of the truck. The maximum spring deflection allowed for the truck wheels is defined in the simulations as  $s=0.15$  m. If the maximum spring deflection reaches this predefined value, the spring rate is doubled (Dr. Steffan Datentechnik, 2025).

In this study, no data from a specific truck make or model were used; instead, the simulations were based on the general characteristics of an N2-category truck. Consequently, the effects of selected parameters on cargo displacement and truck pitch angle were examined.

In the simulations, the intermediate bulk container (IBC) cargo was modeled as a multibody system (MBS). In the multibody model system, the geometric definition of a body is done by semiaxes ( $a$ ,  $b$ ,  $c$ ) (Figure 1). The order of the body is determined by the value of  $n$  (Dr. Steffan Datentechnik, 2025). In the simulations, the body components of the cargo were modeled as hyperellipsoids. We defined a body order of  $n=10$  for the pallet and  $n=9$  for the container.

It should be noted that many other geometric shapes such as spheres, cones, cylinders and capsules may also be used in the construction of these and similar MBS systems (Hittinger & Moser, 2023).



$$\left(\frac{|x|}{a}\right)^n + \left(\frac{|y|}{b}\right)^n + \left(\frac{|z|}{c}\right)^n = 1$$

Fig. 1. Geometric definition of MBS body (Dr. Steffan Datentechnik, 2025)

A further, detailed description of the MBS simulation procedure can be found in the relevant literature (Dr. Steffan Datentechnik, 2025; Moser et al., 2009; Urban et al., 2017).

In the first part of the study, a simulation model of the truck and the cargo were compiled and configured.

Subsequently, the change and the magnitude of the forward movement of the cargo during braking and the pitch angle as a function of the braking deceleration and the vehicle suspension stiffness were analyzed using braking simulations performed with different deceleration values using the truck-cargo complex mechanical system. During the simulation of the truck's motion process, a reaction time of  $t_R = 1.0$  s and a brake delay time of  $t_{bd} = 0.35$  s were taken into account before the braking process began.

### 3. RESULTS AND DISCUSSION

#### 3.1 Vehicle and cargo details in the simulation

In the cargo simulations, the geometry and mass data of a 4x2 truck (N2 category) were taken into account and the simulations were performed with this (Table 1).

Table 1. Truck geometric and mass data used in the simulations

Truck data in the simulation	
Description	value
Length	8.400 m
Width	2.440 m
Height	2.520 m
Wheelbase (A-B)	4.450 m
Front overhang	1.300 m
Track width (Axle A)	2.000 m
Track width (Axle B)	1.850 m
Distance of C.G. (Center of Gravity) from the front axle	1.500 m
C.G. (Center of Gravity) height	0.730 m
Curb weight with driver	5,175 kg

When defining the cargo simulation model, the geometric and mass data of a typical IBC container (Schütz GmbH & Co. KGaA, 2023) were taken into account. In the simulations, the calculations were performed with a fully filled IBC container (Table 2).

Table 2: Geometric and weight data of cargo in the simulation

Geometric and weight data of cargo	value
Overall size (length, width, height)	1.2 m, 1.0 m, 1.16 m
Total weight of cargo	1,055 kg
Geometric shape of the MBS bodies	hyperellipsoid

The cargo consists of a total of 2 bodies with different dimensions and are modeled as an MBS. The individual bodies in the MBS system are connected by fixed joints (DOF=0) as kinematic constraints.

In our modeling, the lower part of the IBC container (pallet) and the bulk body were modeled as hyperellipsoids (Figure 2).

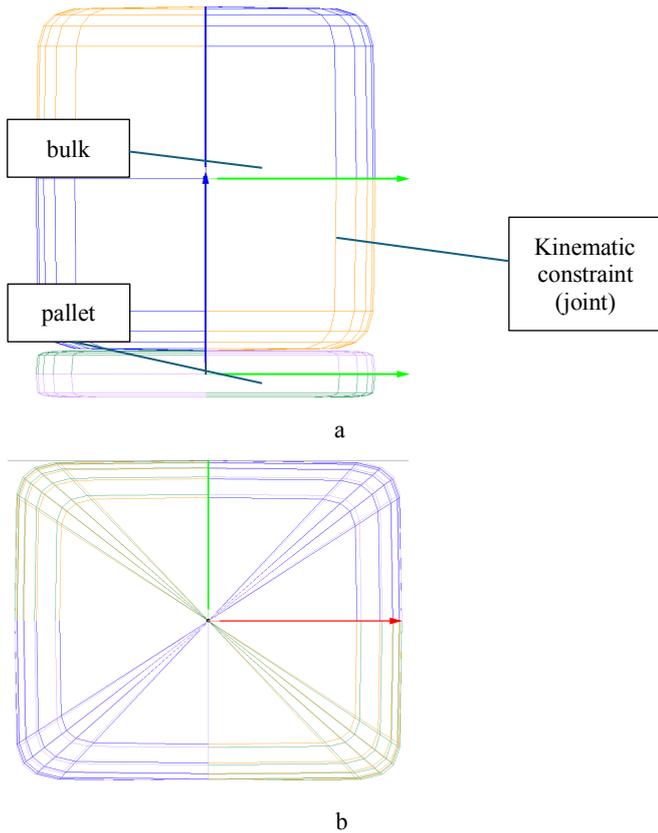


Fig. 2. MBS simulation model of the cargo in PC-Crash (a) front view; (b) top view

The coefficient of friction between the loading surface and the cargo was set to  $\mu=0.55$ . This predefined value allows the extent of load slippage to be examined over a sufficiently wide braking deceleration range. The cargo was positioned on the truck's loading area between the front (A) and rear (B) axles and was not secured by lashing straps or by any other means (Figure 3).

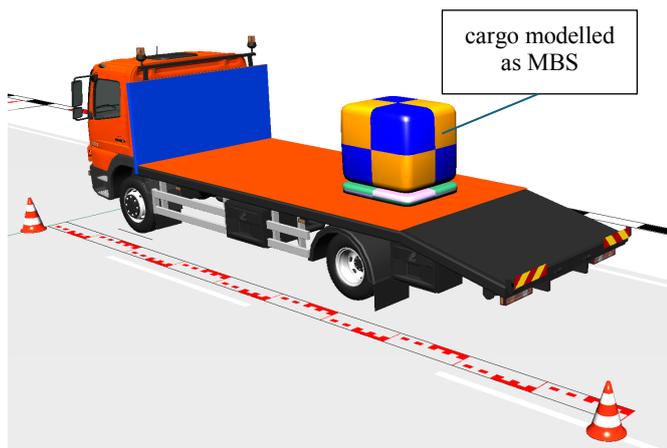


Fig. 3. Assembly of the simulation model of the truck and the cargo in 3D view

The cargo in the simulation model is located in the longitudinal (x) axis of the vehicle, directly in front of the rear (B) axle, at a distance of  $l=4.33$  m from the front axle (Figure 4).

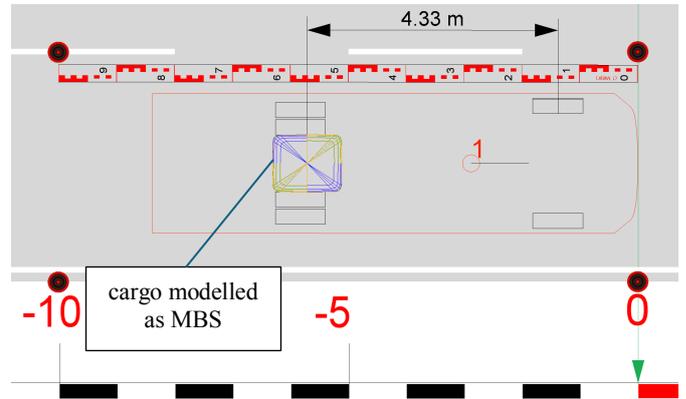


Fig. 4. Assembly of the simulation model in top view

### 3.2 How to conduct simulations

A total of 16 simulations were performed during a parameter study. During this, we performed braking simulations in such a way that the truck simulation model was slowed down from an initial speed of  $v_{0-truck}=40.0$  km/h to a standstill.

During the simulations, we used the braking deceleration ( $a_b=0.8$  g) specified in the regulations EN 12642, Appendix B (Neumann & Dr. Saller, 2025) as a basis and performed simulations using a total of 4 different wheel suspension spring stiffness values, from soft to stiff spring values (Table 3).

Table 3. Suspension stiffness values used in simulations

Spring stiffness characteristics	Spring stiffness category	Front axle (A) spring stiffness [N/m]	Rear axle (B) spring stiffness [N/m]
Soft value	c1	80,000	120,000
Lower-middle value	c2	160,000	240,000
Upper-middle value	c3	240,000	360,000
Hard value	c4	320,000	480,000

After that, the braking deceleration values were reduced in 10% increments (Table 4) and with each reduced deceleration value, the 4 different spring stiffness values were simulated.

Table 4. Braking deceleration values used in simulations

Braking intensity [%]	Braking deceleration [g]	Braking deceleration [m/s <sup>2</sup> ]
100	0.80	7.85
90	0.72	7.07
80	0.64	6.28
70	0.56	5.50

A summary of the simulation calculations with their identification numbers can be found in Table 5.

Table 5. Simulation overview with simulation identification numbers (I.D.)

Simulation I.D.	Spring stiffness category			
Braking deceleration [m/s <sup>2</sup> ]	c1	c2	c3	c4
7.85	1.	2.	3.	4.
7.07	5.	6.	7.	8.
6.28	9.	10.	11.	12.
5.50	13.	14.	15.	16.

### 3.3 Simulation results

The simulations were performed for various spring stiffnesses and braking deceleration values. The results, based on the input data presented in Sections 3.1 and 3.2, are summarized in the following tables. Table 6 presents the simulated values of the forward sliding of the cargo on the loading platform, while Table 7 shows the corresponding truck pitch angle values.

An evaluation of the results indicates that both the maximum cargo displacement and the maximum truck pitch angle value occur for the lowest spring stiffness values and the highest braking decelerations, representing the worst-case scenario.

Table 6. Simulation results: forward sliding (displacement) of the cargo

Displacement of the cargo [m]	Spring stiffness category			
Braking deceleration [m/s <sup>2</sup> ]	c1	c2	c3	c4
7.85	3,22	3,13	3,06	3,03
7.07	2,31	2,10	2,01	2,00
6.28	1,61	1,44	1,38	1,36
5.50	0,43	0,29	0,26	0,25

Tables 6 and 7 also show that both the minimum cargo displacement and the minimum truck pitch angle value occur for the highest spring stiffness values and the lowest braking decelerations, representing the best-case scenario.

Table 7. Simulation results: Pitch angle (rotation) of the truck

Pitch angle of the truck [°]	Spring stiffness category			
Braking deceleration [m/s <sup>2</sup> ]	c1	c2	c3	c4
7.85	1,18	0,64	0,44	0,33
7.07	0,99	0,51	0,35	0,27
6.28	0,82	0,41	0,28	0,21
5.50	0,49	0,25	0,17	0,14

Simulation results are presented in more detail for the worst-case scenario, where the maximum cargo forward movement occurs at the lowest suspension stiffness and maximum braking deceleration.

The individual steps of braking and cargo displacement process are shown in  $t_i = 1.0$  s time increments from the start of the simulation to the final position of the cargo and truck (Figure 5).

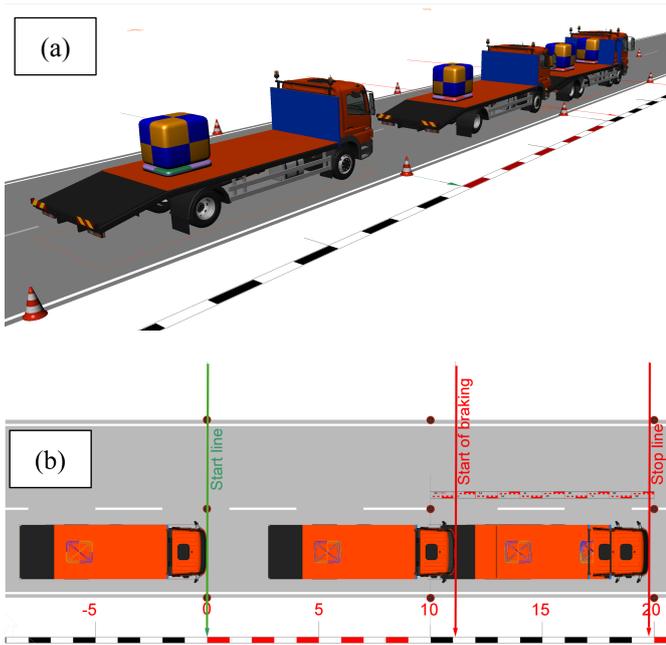


Fig. 5. Maximal cargo displacement in the simulation (simulation I.D.: 1.) from Table 6 and Table 7 ( $v_{0-truck}=40.0$  km/h;  $a_b=0.8$  g) (a) in 3D view and (b) in top view

The maximum forward slip of the cargo was  $s=3.22$  m according to the simulation results (worst-case scenario) (Figure 6).

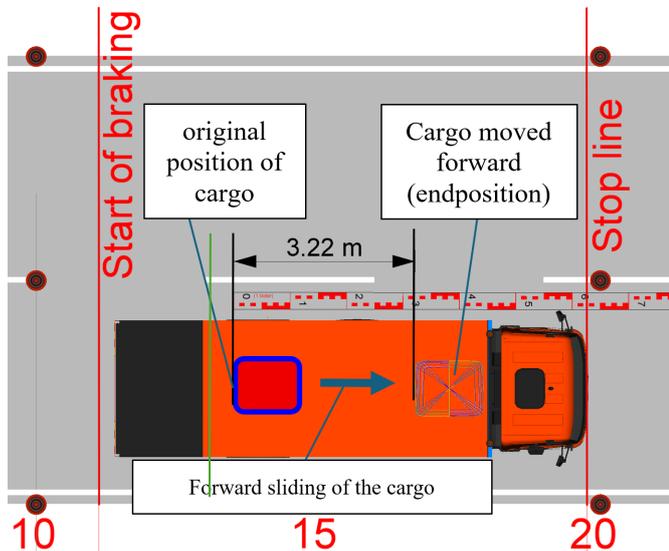


Fig. 6. Forward sliding of the cargo on the truck bed (maximal cargo displacement:  $s=3.22$  m)

The following figures depict key moments of the braking and cargo displacement process. The position of the truck at the beginning of the simulation is shown in Figure 7.

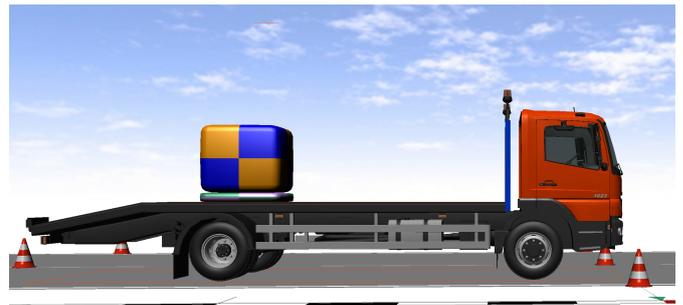


Fig. 7. Position of truck and cargo at the beginning of the simulation (simulation I.D.: 1.) ( $t=0.0$  s;  $v_{0-truck}=40.0$  km/h)

According to the simulation results (Figure 8), the maximum rotation of the truck about the y-axis caused by rear-axle suspension deflection under the cargo mass is  $\theta = -0.63^\circ$  (Figure 10).

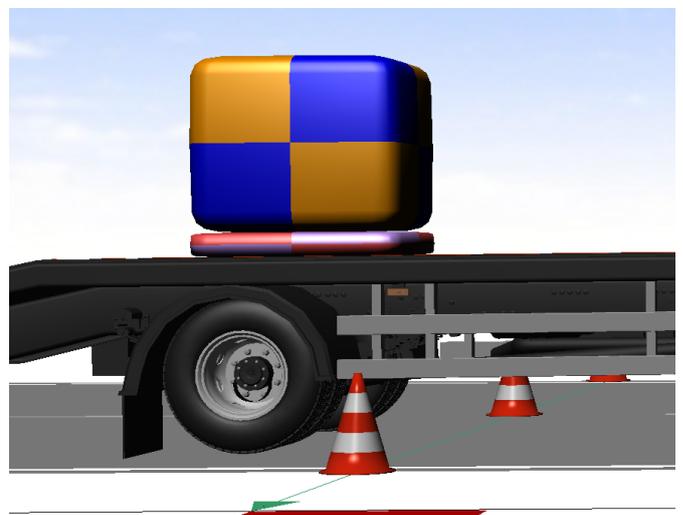


Fig. 8. Position of truck and cargo at maximum spring deflection at the rear wheels in the simulation (simulation I.D.: 1.) ( $t=0.45$  s;  $v_{truck}=40.0$  km/h)

The maximum deflection of the front axle wheel springs occurred at the moment the truck came to a standstill, i.e. at the end of the braking process (Figure 9).

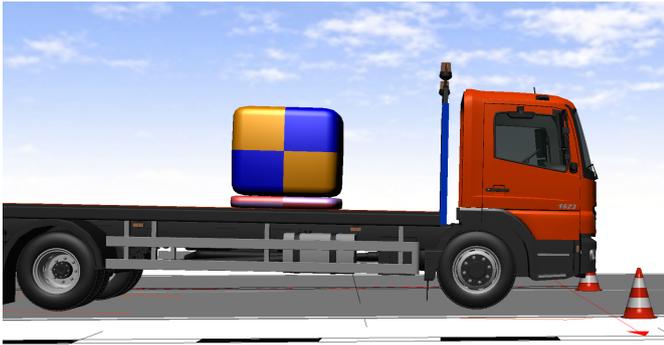


Fig. 9. Position of truck and cargo at maximum spring deflection at the front wheels in the simulation (simulation I.D.: 1.) ( $t=2.51$  s;  $v_{truck}=0.1$  km/h;  $v_{cargo}=12.0$  km/h)

At this time, the truck's pitch angle was  $\theta=1.18^\circ$ , which is also the maximum pitch angle (Figure 10). At this moment, the cargo was still moving and sliding forward on the truck's loading platform at a speed of approximately  $v_{cargo}=12.0$  km/h.



Fig. 11. Position of truck and cargo at the end of the cargo sliding process (simulation I.D.: 1.) ( $t=3.14$  s;  $v_{truck}=0.0$  km/h;  $v_{cargo}=0.1$  km/h)

The simulation results (measurement points) for cargo displacement (Figure 12) and for the pitch angle (Figure 13) can best be approximated by a three-degree polynomial.

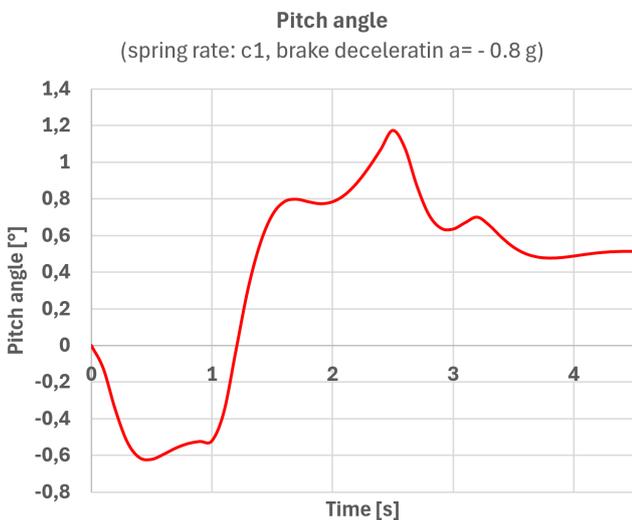


Fig. 10. Simulated pitch angle at minimum spring rate stiffness (c1) and maximum brake deceleration ( $a = -0.8$  g)

The forward sliding of the cargo on the loading surface stopped at  $t=3.14$  s from the start of the simulation. At this time, the truck's pitch angle was  $\theta=0.69^\circ$ , which decreased even further in the later phase of the simulation. The cargo reached its final position at a distance of  $l=0.08$  m from the front wall of the truck's loading platform, and there was no collision with the front wall (Figure 11).

Cargo displacements for different spring rates

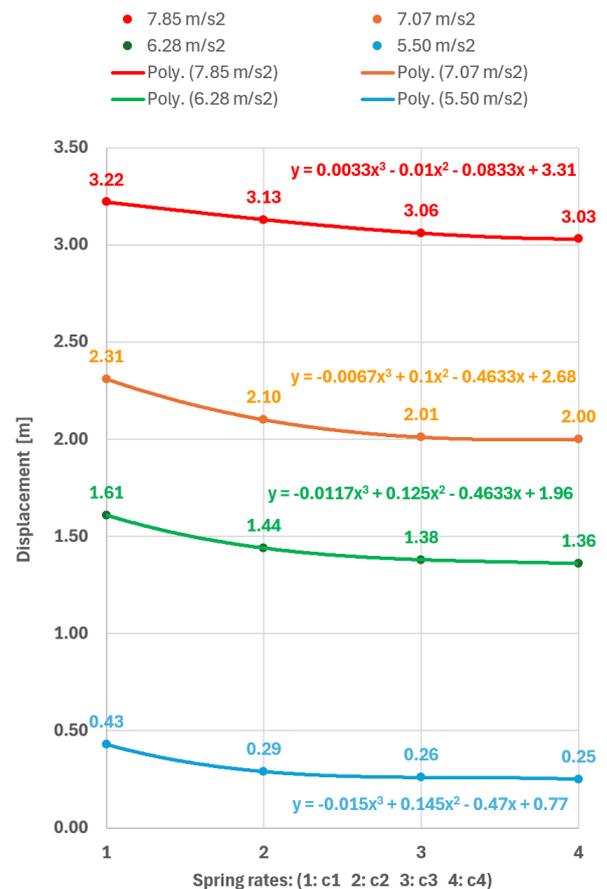


Fig. 12. Simulation results (measurement points) and their approximation with polynomial for cargo displacement

Based on the evaluation of the pitch angles values, it can be concluded that the higher the suspension stiffness values at the truck wheels, the smaller the pitch angle reduction when the braking deceleration is reduced (Figure 13).

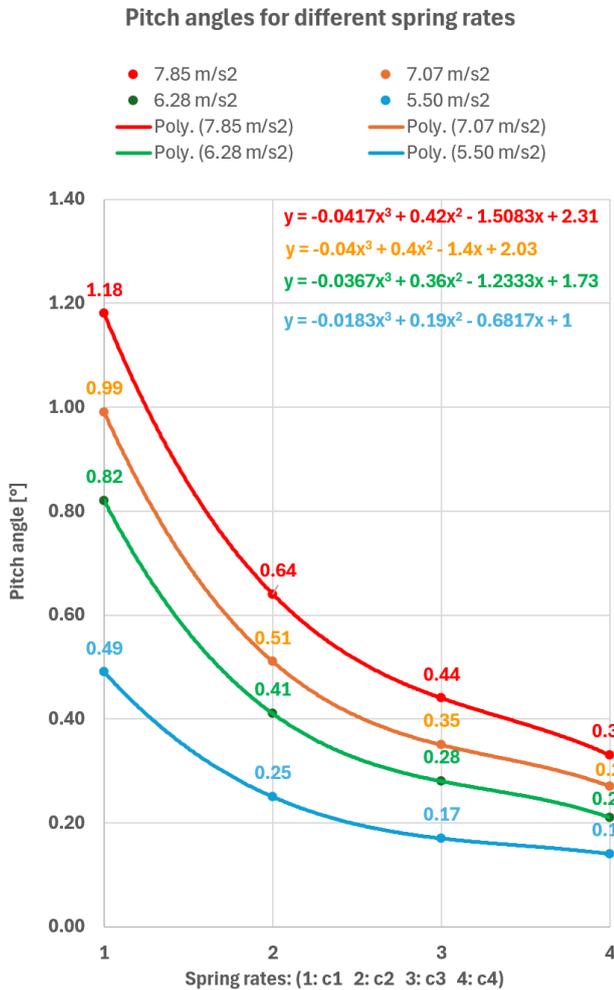


Fig. 13. Simulation results (measurement points) and their approximation with polynomial for pitch angle of the truck

Based on the evaluation of the truck pitch angle, it is evident that changing the Soft value (c1) spring stiffness to the Lower-middle value (c2) causes the largest reduction (0.54) in the maximum values of the pitch angle related to braking. Changing from c2 to c3 and from c3 to c4 causes significantly smaller pitch angle reductions (0.2 and 0.11) (Figure 14).

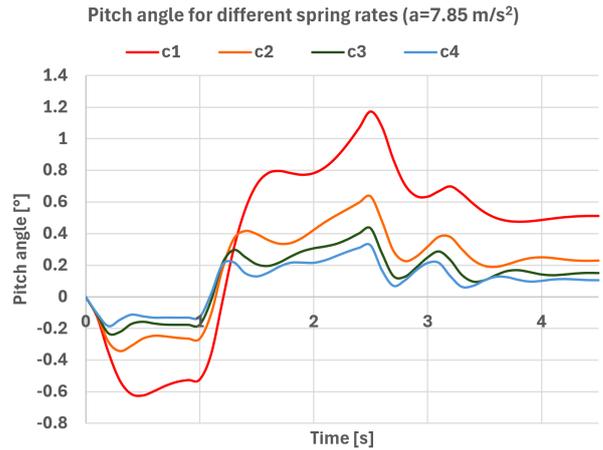


Fig. 14. Simulated pitch angles for different spring rates at braking deceleration of  $a=7.85 \text{ m/s}^2$

Pitch angle diagrams for all simulations can be found in appendix 1.

#### 4. LIMITATIONS OF THE SIMULATION MODEL

The cargo model (multibody model) discussed in this research is not able to model the dynamic displacement of the liquid in the IBC container. The mentioned dynamic fluid displacement can occur, for example, during acceleration, braking, cornering, vertical road excitation, or during a collision accident. In addition, permanent deformation of the cargo and the truck cannot be modeled in the event of mutual contact. This limitation applies, for example, when the cargo slides on the loading platform due to a dynamic maneuver or a collision and hits the structural elements of the truck's loading platform

#### 5. CONCLUSIONS AND PLANNED FURTHER RESEARCH

Based on the evaluation of the simulation results, it was concluded that the largest cargo displacement and a largest pitch angle value at the truck occurred with the lowest spring stiffness values and the highest braking decelerations. This case can be classified as a worst-case scenario.

The simulation results also showed that the higher the suspension stiffness values at the truck wheels, the smaller the pitch angle reduction when the braking deceleration is reduced.

According to the simulation results, the maximum forward slip of the cargo in the worst case (simulation I.D.:1). was  $s=3.22 \text{ m}$ . In this case, the truck's pitch angle was  $\theta=1.18^\circ$  (maximum pitch angle) when the truck comes to a stop after braking. At this moment, the cargo was still moving and sliding forward on the truck's loading platform at a speed of approximately  $v_{\text{cargo}}=12.0 \text{ km/h}$ .

Based on the evaluation of pitch angle of the truck, we have determined, that changing the Soft value (c1) spring stiffness category to the Lower-middle value (c2) causes the largest reduction (0.54) in the maximum values of the pitch (braking). According to the results, changing from c2 to c3 spring stiffness category and from c3 to c4 spring stiffness category

causes significantly smaller pitch angle reductions (0.2 and 0.11)

The relationships and experience obtained in this study for cargo displacement and pitch angle will help to evaluate the upcoming validation of the recently developed MBS lashing strap simulation model (Ignacz et al., 2025). These validation tests and the corresponding simulations involve loads placed on the truck bed under intensive braking conditions. Accordingly, they evaluate both the cargo displacement during braking and the resulting truck pitch angle values.

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### Appendix A. Simulated pitch angles values

