Advances in Science and Technology
Research Journal

*Advances in Science and Technology Research Journal* 2024, 18(4), 312–328
https://doi.org/10.12913/22998624/189613
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Received: 2024.04.25
Accepted: 2024.06.05
Published: 2024.06.20

# Investigating Vibration Transmission in Cargo Containers During Heavy-Duty Off-Road Transport

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## ABSTRACT

This article focuses on the investigation and analysis of vibrations transmitted to cargo during off-road transportation, with particular emphasis on the impact of vehicle and road surface interactions. The primary objective of the research is to quantify and characterize the amplitudes of vibrations generated by the interaction between heavy-duty truck tires and rough terrain, and their subsequent transmission to cargo containers. To achieve this, a virtual model of a tactical transportation truck was created using TruckSim software. Two characteristic off-road tracks were simulated, based on driving conditions typically experienced by heavy-duty vehicles in demanding logistical scenarios. The experimental validation of the virtual model was conducted using a heavy-duty truck outfitted with a 20 ft (6096 mm) cargo container. The results of the work include recorded acceleration data, suspension behavior, and the maximum driving speed at which the vehicle remained stable on both tracks. Moreover, the work is a direct response to the needs of the automotive industry and the military.

**Keywords:** simulation, modelling, heavy-duty transport, suspension, vibrations, signal processing, accelerometers.

## INTRODUCTION

Vibrations induced to cargo during transportation occur due to the movement of the cargo and the vehicle transporting it. They can be caused by several factors such as uneven road surfaces, acceleration and braking forces, vehicle suspension, cargo loading and unloading and external forces such as wind or turbulence. In general, vibrations induced during transportation can cause damage or even destruction of the cargo. Possible damage caused during transportation can result in financial losses. The transport itself plays an important role in the economy [1–2] as well as playing an important role in logistics support [3–4]. For cargo related to military transportation, any delay caused by damage to cargo can impact mission readiness and the ability to execute the mission. It can also cause damage to military vehicles and equipment, leading to increased maintenance costs and delays. In conclusion, proposed vibration research is important inter alia to ensure the safety of personnel, equipment and supplies, increase mission readiness and optimise cost-effectiveness.

Issues concerning vibrations induced to cargo during transportation are the subjects of scientific articles. Article [5] focuses on the study of vibrations generated by trucks during off-road transportation. The author used an accelerometer to measure vibrations in different directions. The results of the study showed that the vibrations were most intense in the vertical direction. Off-road conditions also generate higher and more variable vibration levels compared to on-road conditions, which can lead to increased risk of damage to the cargo Article [6] conducted a study using various road types and cargo securing methods, including lashing straps and anti-slip mats. The results of the study showed that, when transporting hazardous items (Army ones), e.g. ammunition, appropriate cargo securing is crucial. Other specialists have also approached concerns in this field. Hence, paper [7] analyses the level of vibrations inside a container destined for transporting products made of glass, as well as a comparative analysis of vibration level when the truck is equipped with leaf spring suspension or pneumatic solution. In this case, the truck was driven on a tarmac road, and driving speed was taken into consideration on the mentioned type of road.

The study detailed in [7], about experimental tests concerning the transported cargo, offered useful information regarding the approach but, due to the fact that the trucks moved on public roads, the results cannot be extrapolated in the case of logistic transportation vehicles which are equipped with more rigid suspension. In addition, military transportation trucks also run on unpaved roads, which implies increased mechanical stresses. That is why the study took into account testing requirements for military vehicles, both on unpaved and paved roads, imposed by military standard STANAG 4370 [8].

The article [9] shows that vibration values can vary significantly for different means of transport, which in special cases can lead to damage during transport. It is therefore particularly important to adapt packaging to specific transports in order to mitigate possible transport damage. In turn, the study [10] discussed the vibration levels occurring in parcels transported by small and medium-sized trucks and cars. The work highlights the importance of the process of designing packaging that is resistant to vibrations at specific frequencies in order to ensure the safe delivery of goods. Similar research [11] focused on vibration studies of large shipping containers during truck transport. In addition to using durable packaging systems, properly designed suspension has to be provided to protect the load from the varying levels of vibration that occur during truck transport. The work [12] indicates that road conditions create significant stresses on the chassis, requiring the use of modern materials and construction techniques to increase the durability and performance of vehicle chassis. In the described field, some researchers also use advanced signal processing techniques, including the article [13] analyzed vibrations occurring in trucks during off-road transport using wavelet analysis, with particular emphasis on military loads. The issue of the safety of transported cargo also concerns ensuring the possibility of locating trucks and transported loads. The paper [14] presents a sensor fusion technique for locating trucks using Global Positioning System (GPS) and Radio Frequency Identification (RFID) in closed environments. The study focuses on improving the location accuracy of container trucks in port environments. Research shows that combining the above technologies results in a more reliable and precise location than using individual technologies. The results of other studies also show that a modern research direction is the use of radio technologies, i.e. Ultra Wideband, to locate objects in open and closed environments [15].

Due to the large number of presented factors that may have an impact on mentioned vibrations, conducting experimental research on their impact on the cargo is complicated and extremely expensive. Therefore, for the vibration analysis produced by the interaction between tires and rolling track [16], it is useful to model a truck for logistic transportation. Having the model, its motion can be simulated either over a single or multiple road obstacle before conducting any experimental tests, since such vehicles are destined to run not only on paved but also on unpaved roads. An example of software for simulating the considered phenomena is TruckSim. TruckSim is used for both civilian and military vehicle simulations, but the simulations carried out for military vehicles are limited to standardised tests, such as cross slope sine sweep test, handling test, stability test, steering test etc.

Moreover, the effects on transported goods and equipment while passing over single and multiple obstacles have not been addressed in the specialised literature. They have been referred only to the way they are affected when travelling on paved roads with general purpose trucks. Thus, they cannot be extrapolated to the military vehicles for logistic transport, equipped with stiffer suspensions. Hence, the discussed research represents a new approach addressing tests like passing over single and multiple obstacles.

The article focuses on designing, developing, and implementing, with the use of mechanical simulation software (TruckSim), two rolling tracks specific to logistical transportation vehicles while running in a tactical field (road with single and multiple obstacles). The novelty consists of using military standards to model obstacle-based tracks; the geometrical modeling of obstacles specific to Aberdeen Proving Groundstrack (APG) was performed by generating a matrix based on these obstacles. In order to verify the results of simulation tests six accelerometers were mounted on the vehicle, to record accelerations during driving.

The relevance of the work presented in this article consists in analysing vibration parameters resulted from off-road transportation of goods, such as amplitude, and determine the limit values of driving parameters. It is important to establish these characteristics due to the specific requirements of military transportation such as the need to ensure cargo integrity and safety, the need for operational readiness (meaning that the vehicles, weapons, and other critical systems remain operational and do not suffer from vibration-induced malfunctions), as well as for logistical and strategic considerations (understanding how different terrains impact vibration levels can aid in route planning, ensuring that cargo is transported via paths that minimize risk and potential damage or help in preparing vehicles and cargo for various conditions, if possible, enhancing adaptability and mission success).

## MATERIALS AND METHODS

### Theoretical background

During vibrations, the mechanical energy is dissipated by the damping phenomenon. This limits the movement amplitude, decreases the amplitude of free vibrations and introduces delays between excitation and response. Unlike mass and rigidity, the damping degree cannot be computed. Therefore, the suspension of the vehicle is one of the most important systems that ensures the decrease of vibrations generated by the interaction between the vehicle tyre and the rolling track, with a positive influence on passenger comfort, vehicle stability and cargo protection.

One of the models used to study vehicle stability is the quarter-car system with two degrees of freedom. The so-called quarter car system is composed of two bodies: sprung (car) and unsprung (suspension, wheel, tire) mass. Although it is a simplified model, stiffness and damping are taken into consideration. Thus, between the road and the suspension, the stiffness and damping of the tire and wheel are considered, and between the suspension and the car, the stiffness and damping of the spring and damper are considered. Mathematically, the elastic system with two degrees of freedom allows modelling the quarter–car model [17], depicted in Figure 1.

Discussed model is composed of:

- sprung mass $m_s$, which rests on suspension elements;
- unsprung mass $m_{ns}$, which supports suspension elements;
- coil spring (elastic part) which constitutes the connection between the two parts and whose rigidity is $k_s$;
- spring (elastic system, tyre), whose rigidity is $k_p$;
- viscous damping element (damper) with damping coefficient of $c_s$;
- $s$ – kinematic excitation (uneven rolling tracks);
- $z_s$, $z_{ns}$ – vertical movement of sprung and unsprung mass, respectively.

The differential equation of movement for the two masses, under the influence of perturbation forces is:

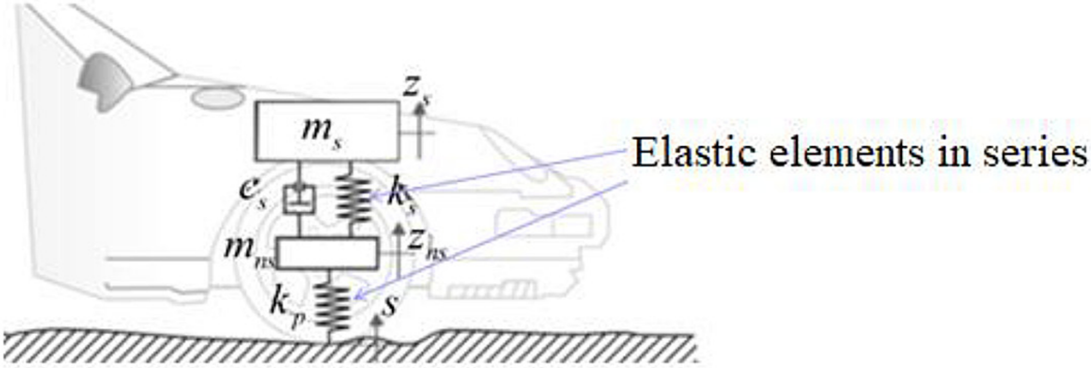


**Figure 1.** A diagram of the quarter-car model

$$m_{ns} \cdot \ddot{z}_s - c_s \cdot (\dot{z}_s - \dot{z}_{ns}) - k_s \cdot z_s + z_{ns} \cdot (k_s + k_p) = k_p \cdot s \qquad (1)$$

The frequencies of oscillation of the vibrating system with two degrees of freedom can be expressed as:

$$\omega^2_{1,2} = \frac{1}{2} \cdot \left[ \frac{k_s + k_p}{m_{ns}} + \frac{k_s}{m_s} \pm \sqrt{\left(\frac{k_s + k_p}{m_{ns}} - \frac{k_s}{m_s}\right)^2 + \frac{4 \cdot k_s^2}{m_s \cdot m_{ns}}} \right] \qquad (2)$$

An increasing rigidity of sprung mass can lead to an increased equivalent elastic constant and to an increased suspension's proper frequency. The such later increase can also result from accelerations generated by uneven rolling tracks, which is why the resonance must be avoided. According to [18], recommended values for suspension's proper frequency are between 1 and 1.3 Hz. In Figure 2, it can be observed the importance of unsprung mass in reducing the intensity of perturbation forces. Knowing that the damping ratio is expressed as [19]:

$$\zeta = \frac{c}{2\sqrt{k \cdot m}} \qquad (3)$$

where: c – actual damping and $2\sqrt{k \cdot m}$ – critical damping coefficient.

It results that a decrease of unsprung mass can lead to an increase of damping ratio, contributing, as depicted in Figure 2a, to a decrease of the maximum value for 10 Hz frequencies.

In turn, in the case of a sprung mass (Figure 2b), vertical acceleration has higher transmissibility rates for lower frequencies and lower damping ratios. According to [18, 19], the recommended values for the damping ratio are between 0.2 and 0.4. Higher values of vertical acceleration transmissibility lead to the necessity of a rigid suspension, which has one oscillation for the sprung mass, thus resulting in an asymmetrical characteristic of the damper.

## Simulation research

Simulation tests are designed to quickly test various variants of vehicle motion and analyse occurring vibrations. Several objectives were adopted for the simulation research:

- to determine maximum values of longitudinal accelerations in the vertical and lateral plane [20, 21], which are recorded in six points on the truck by mounting six accelerometers within the simulation, used to estimate the damage degree of transported cargo;
- to analyse functioning characteristics of suspensions used within logistic transportation vehicles while driving on unpaved roads;
- to estimate the maximum driving speed for which the roll or pitch angle of a vehicle does not lead to stability loss or damage of transported cargo.
- for the suspension of transportation vehicles, if using the system with two degrees of freedom to analyse its mechanics, the following can be observed:
- it is a complex and realistic model, allowing a rapid analytical calculus of functional characteristics,
- if the non-linear behaviour of tyre and hydraulic damper characteristics is considered, the differential equation system cannot be put to an analytical integration, which involves the use of modelling and simulation software.

TruckSim simulation software was used, to have a more overall view of the suspension behaviour when mounted on a truck, running on unpaved roads, which is specific to military logistic transportation, but also to estimate the maximum driving speed [22] without damaging the cargo. The aforementioned software can be used to model the rolling track, heavy-duty truck

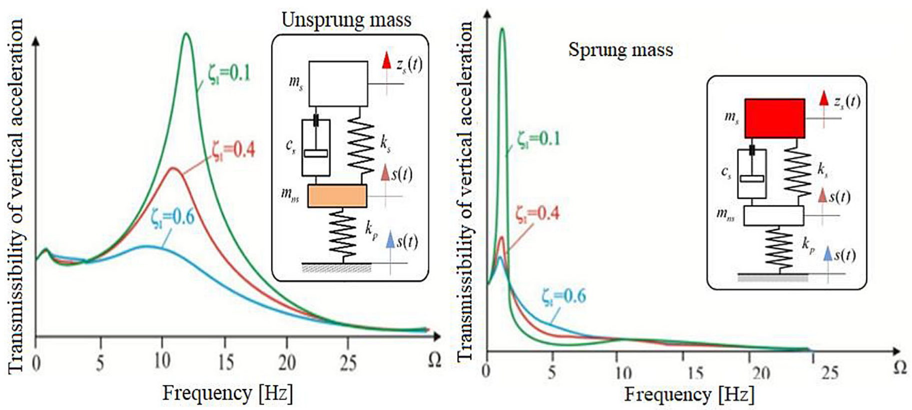


**Figure 2.** Transmissibility characteristics for elastic elements in series (a) and for sprung mass (b)

(the suspension, engine power, number and type of axles, type of container, cargo mass etc.) can be selected, as well as driving speed (which can be constant or variable by actuating the braking or throttle system) [23]. Within the software, a leaf spring suspension was modelled, specific to military transportation vehicles, with the main front/rear parameters: mass of 5.5t/8.5t and displacement of ±150 mm/ +100 mm [23–24]. Leaf springs are widely used for cargo transportation vehicles, but also for automobiles. This type of elastic element has some advantages: it is technologically simple, cheap, it takes over the longitudinal forces acting on the axle (thus simplifying the manufacturing layout), it is highly maintainable, and has a high damping effect due to friction between leaves etc. The main drawback of the leaf spring suspension is the increased weight i.e. the leaf spring most often is the heaviest of all elastic elements. The modelled truck used for simulation purposes had similar technical parameters with the one submitted to further experimental tests. The vehicle consisted of a chassis and a 20 ft standardised container for cargo transportation, with a total mass of 6.2 tons [25], so the simulation is similar to real military logistical transportation.

Accelerations transmitted to the truck while driving on unpaved roads were measured with the use of six accelerometers mounted by the same setup as during experimental tests. Thus, four accelerometers were mounted on the container corners each having one accelerometer. One accelerometer was placed under the container in the longitudinal plane of symmetry while the sixth one was placed on the front axle, as depicted in Figure 3 (except for the sixth one, which is not visible due to the position relative to the vehicle).

In order to position all mentioned accelerometers within the software in accordance with the aforementioned setup, the dimensional parameters of both the chassis and the container need to be known. Each pair of coordinates (x, y, z) was set in regard to a global coordinate system, whose origin was established in the vehicle's median plane delimited by the two contact areas between front tires and ground. Hence, the coordinates of all six accelerometers used within the simulation software are presented in Table 1.

Next step consisted in the modelling process of a single obstacle track [26]. In the TruckSim library, there is already a predefined procedure, called "small bump", but the dimensional characteristics of obstacles are different from those used during experimental tests (trapezoidal obstacle specific to APG track), which is why it was modelled an obstacle with the sizes presented in Figure 4a. For the modelling process of the driving track, there have been introduced dimensional characteristics, as depicted in Figure 4b.

There have been established both obstacle sizes and frontal distance between them (Figure 4, where is presented the 2D shape of a modelled track). For a better understanding of the rolling track, in Figure 5a there are presented three modelled obstacles and their layout site. The

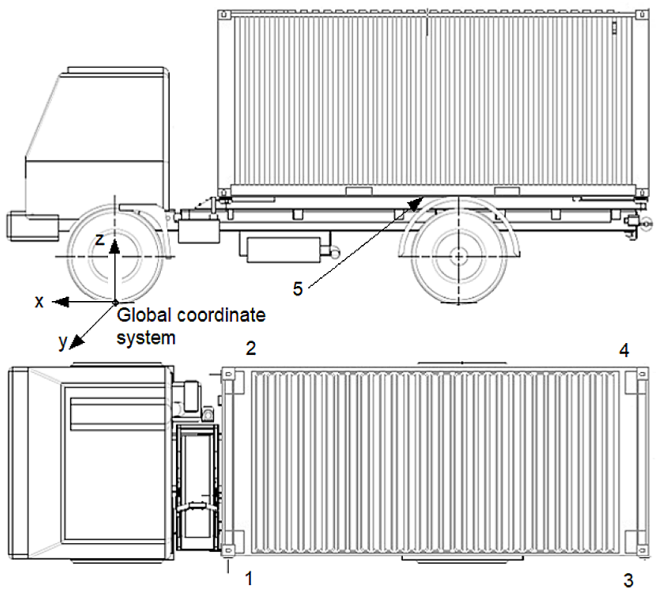


**Figure 3.** Accelerometer setup on the truck

**Table 1.** Coordinates of deployed accelerometers

| Accelerometer | X | Y | Z |
|---|---|---|---|
| | (mm) | | |
| 1 | -1600 | 1175 | 1200 |
| 2 | -1600 | -1175 | 1200 |
| 3 | -7579 | 1175 | 1200 |
| 4 | -7579 | -1175 | 1200 |
| 5 | -1103 | 1175 | 1200 |
| 6 | 0 | 0 | 510 |

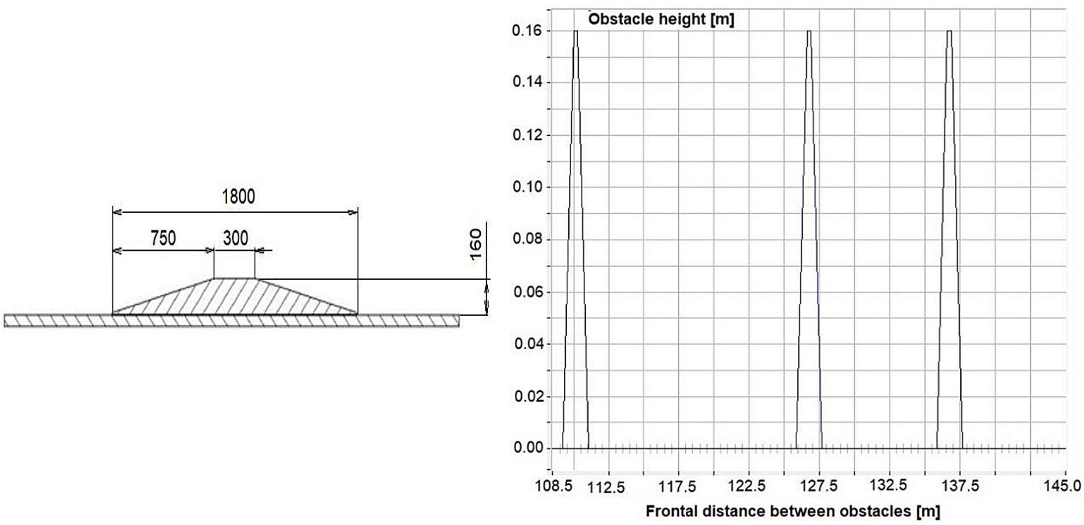


**Figure 4.** Parameters of the obstacles for single obstacle size (a) and 2d shape of modelled track (b)

distance between the first and second obstacle is 14.8 m and between the second and last one is 8.2 m. The truck movement was performed at different constant speeds (5 km/h, 8 km/h and 10 km/h), without the use of braking or accelerating systems.

Next step consisted in modelling the multiple obstacle track [27]. The software library contains a testing procedure called ”left/right bumps”, yet the dimensional characteristics of obstacles and the layout pattern are also different from the ones used within the APG track, which is why it was modelled a new track with characteristics as depicted in Figure 4b, with values that describe obstacles height, length, width, as well as the lateral and frontal distance between them. Nevertheless, due to some restrictions of the simulation software, only the first three series of obstacles have been modelled, as depicted in Figure 5b.

The truck movement was performed at different constant speeds (3.5 km/h, 5.5 km/h and 7.5 km/h), without the use of a braking or accelerating system. The program was set to actuate the steering gear after each obstacle so that the vehicle can pass over every obstacle. Otherwise, after the first obstacle, the truck would tend to drive outside the rolling track.

## Experimental research

The experimental study was conducted on a truck belonging to the Romanian Armed Forces, equipped with a 20 ft container, mainly used for [28] transportation of command centres and containerized transportation of equipment (Figure 6).

Considering the main purpose of the experimental research, which is measuring characteristics of vibrations in six points of the container during truck movement [29] on different road categories, the tested vehicle was equipped with several devices as further detailed.

For the measurement of accelerations on three axes, along with temperature and humidity within the container, it was used a measuring device type Lansmont SAVER model SV-1. The device is mounted on the container floor, at the rear

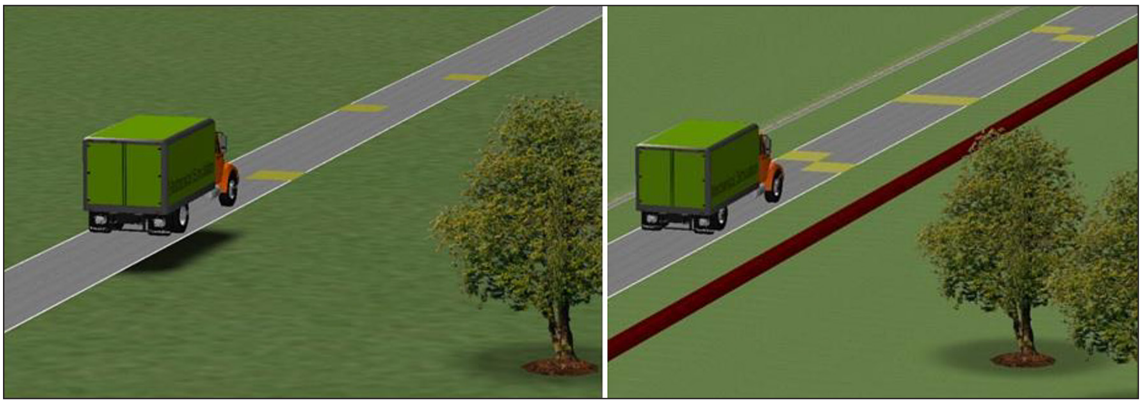

**Figure 5.** Modelled tracks in TruckSim with a single obstacle (a) and multiple obstacles (b)

**Figure 6.** Containerized truck during tests

part, because previous studies such as [14] have shown that in that area are recorded the highest level of vibrations. The minimum sample rate was 651 samples/second, and the sample interval included 1024 values. During tests, there were used piezoelectric accelerometers with embedded vibration preamplifiers. Their specification is presented in Table 2.

Also, data acquisition was made with the Iotech 650u system with signal conditioning. The main advantage of this system is the possibility to use it without a power supply, being connected through USB during data transfer. For data acquisition and processing, a PC was used. Also, the computer was used to install the required software, for connection with data acquisition systems, VBOX video and GPS VBOX 3i video.

Therefore, the main software used for the above-mentioned devices are as follows:

- DasyLab [23] – for data acquisition and signal conditioning;
- VBOX Tools – for operating the GPS, visualising and analysing recorded data;
- VBOX video – for video recording and data analysis.

Recorded data have been analysed with the use of dedicated software, which calculates statistical values, as well as acceleration [30]. Each test was performed with the use of GPS systems and data interpretation was performed by taking into account driving conditions provided by the video system, truck dynamics resulting from the GPS, towards the 3D position of the truck and moving speed. To determine

**Table 2**. Main characteristics of the accelerometers

| Accelerometer / Specification | Triaxial accelerometer PCB 356A25 | Piezoelectric accelerometer PCB 355B33 |
|---|---|---|
| Sensitivity | 25 mV/G | 25 mV/G |
| Measuring range | ±200 G | ±50 G |
| Measuring frequency | (±5%): 1-5000 Hz | (±5%): 2-5000 Hz |
| Non-linearity | ≤ 1% | ≤ 1% |

**Figure 7.** Weighing procedure for the truck rear axle

the mass characteristics of the tested truck, a weighing platform with an indicator, type DF-WKRP (Figure 7) was used.

The setup of all six accelerometers was the same as during simulation research: four accelerometers at the container corners (two at the rear part and two at the front part), and one accelerometer on the median plane, along the longitudinal axis of the container. The sixth accelerometer was installed on the front axle. Accelerometer numeration was according to Figure 3 so that thereafter, the corresponding accelerations recorded by each sensor are presented with the same numeration: 1, 2, 3, 4, 5.

The rest of the equipment used during experimental research [31, 32], such as the GPS, video recording system of data (Video VBOX) and data acquisition and signal conditioning were installed in the truck's cabin. The container was filled with sandbags up to reaching the maximum load capacity of the truck. Also, mentioned sandbags were positioned so that the centre of mass was identical to that of a container equipped as a command centre. In the case of military tactical trucks destined for the transportation of sensitive equipment, the functional situation is when the road category has one obstacle on the way. This type of road implies that while one of the wheels belonging to an axle keeps the horizontal trajectory, the other wheel, of the same axle, passes over an obstacle. According to [33] such a road used for testing is standardised. Also, as well as in the case of single obstacle roads, the testing procedure on roads with single and multiple obstacles is standardised, according to [34]. It implies the existence of several obstacles, positioned both to the left and right of the rolling track, staggered or not, so that the wheels of the same axle can pass simultaneously over the obstacles or at short time intervals apart.

In this case, the truck is also submitted to roll and lift movement, the latter when both wheels pass simultaneously over the obstacle. Regarding the testing track used during experimental tests, the layout of obstacles is depicted in Figure 8. The test was performed twice and accelerations were measured in each of the six points.

**Figure 8**. The layout of obstacles for single obstacle road (a) and multiple obstacle road (b)

## RESULTS

### Simulation results

The current subsection is divided into two parts: results for simulation with a single obstacle and with multiple obstacles.

#### *Single obstacle*

For the single obstacle road simulation, three constant driving speeds have been arbitrarily chosen: 6 km/h, 8 km/h and 10 km/h, since over 10 km/h, on such road categories, high values of vertical acceleration occur, which may lead to damaging the transported cargo. The example depicted in Figure 9 represents the time variation of accelerations measured by accelerometer number 5 while driving with a constant speed of 10 km/h.

The simulation scenario was set to actuate the steering gear after each obstacle so that the vehicle can pass over subsequent obstacles. Otherwise, after the first obstacle, the truck would tend to drive outside the rolling track. During the simulation, the pitch movement of the vehicle was also analysed, which is common to appear while driving on such roads (Figure 10).For the same constant driving

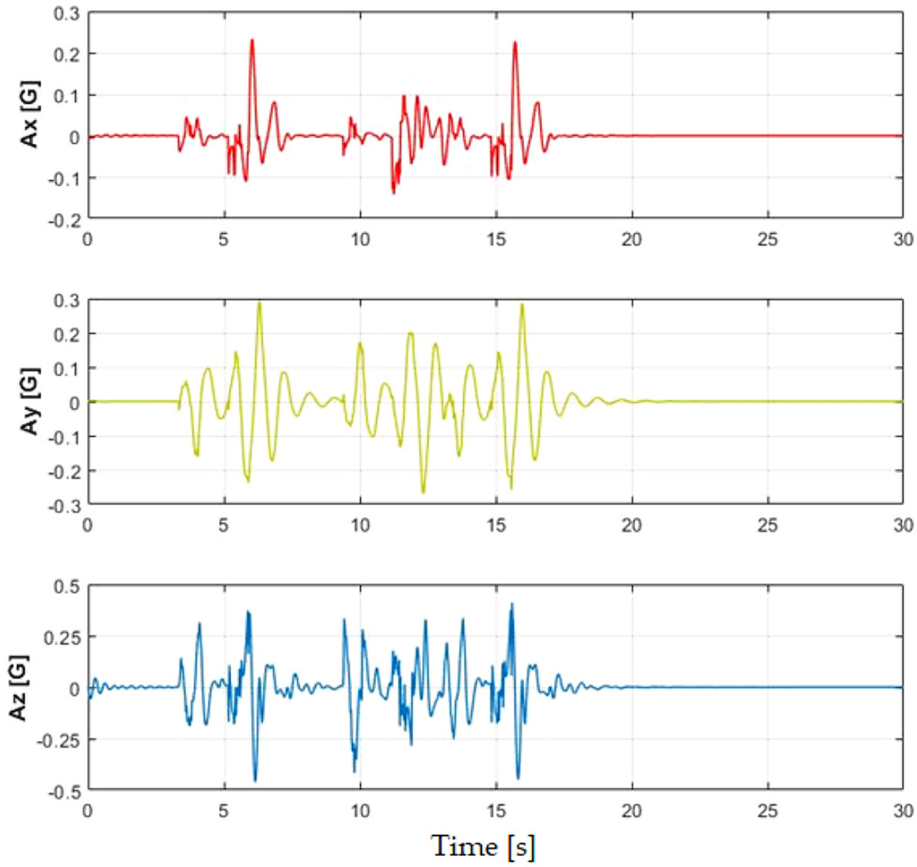


**Figure 9.** Time variation of accelerations measured by accelerometer number 5 while driving with a constant speed of 10 km/h

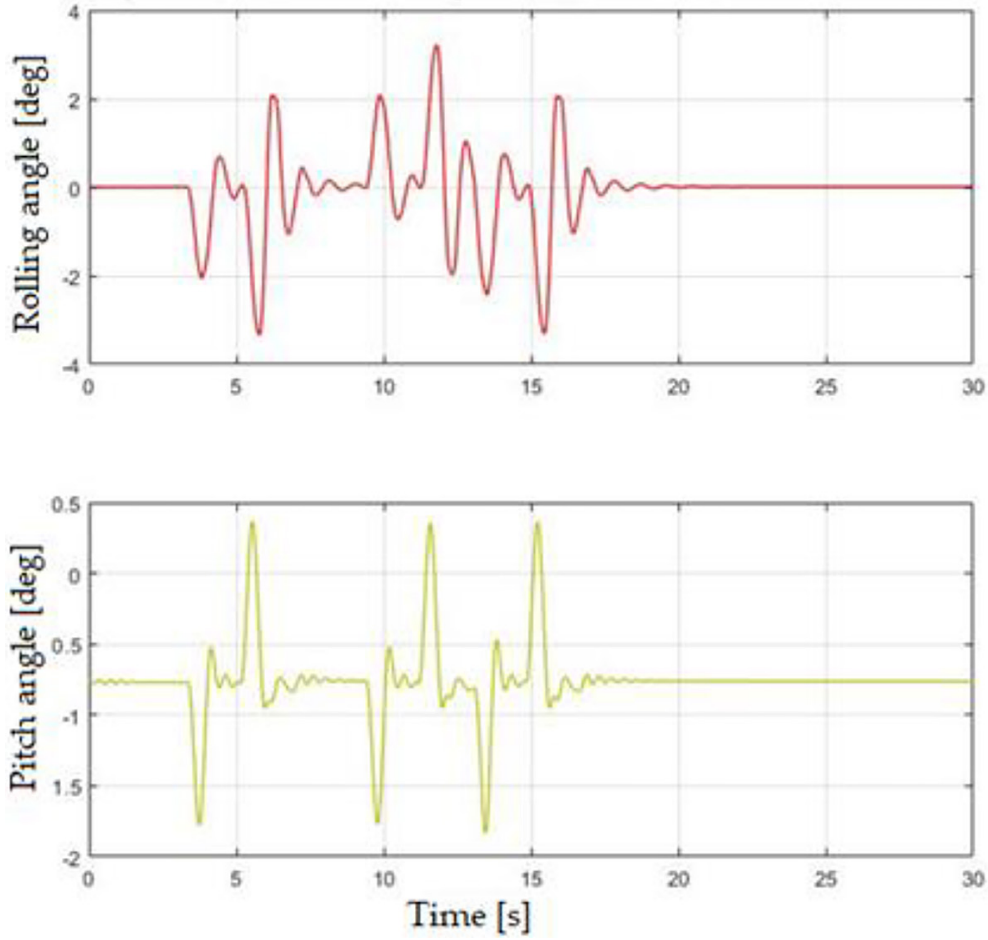


**Figure 10.** Time variation of rolling and pitch angle of the sprung mass

**Table 3.** Maximum and minimum values of accelerations

| Speed [km/h] | Measuring point | Maximum [g] | | | Minimum [g] | | |
|---|---|---|---|---|---|---|---|
| | | X | Y | Z | X | Y | Z |
| 6 | 1 | 0.12 | 0.19 | 0.26 | -0.11 | -0.22 | -0.26 |
| | 2 | 0.11 | 0.20 | 0.35 | -0.14 | -0.22 | -0.31 |
| | 3 | 0.12 | 0.42 | 0.54 | -0.11 | -0.46 | -0.43 |
| | 4 | 0.11 | 0.42 | 0.73 | -0.14 | -0.46 | -0.45 |
| | 5 | 0.12 | 0.20 | 0.27 | -0.11 | -0.23 | -0.25 |
| | 6-front axle | 0.12 | 0.25 | 0.22 | -0.15 | -0.22 | -0.18 |
| 8 | 1 | 0.11 | 0.29 | 0.37 | -0.11 | -0.30 | -0.38 |
| | 2 | 0.13 | 0.29 | 0.37 | -0.12 | -0.30 | -0.37 |
| | 3 | 0.11 | 0.45 | 0.80 | -0.11 | -0.45 | -0.46 |
| | 4 | 0.13 | 0.45 | 0.82 | -0.12 | -0.45 | -0.58 |
| | 5 | 0.11 | 0.29 | 0.36 | -0.11 | -0.30 | -0.38 |
| | 6-front axle | 0.09 | 0.32 | 0.30 | -0.15 | -0.31 | -0.26 |
| 10 | 1 | 0.23 | 0.29 | 0.45 | -0.14 | -0.27 | -0.46 |
| | 2 | 0.23 | 0.29 | 0.39 | -0.15 | -0.27 | -0.39 |
| | 3 | 0.23 | 0.52 | 0.95 | -0.14 | -0.51 | -0.68 |
| | 4 | 0.23 | 0.52 | 0.82 | -0.15 | -0.51 | -0.78 |
| | 5 | 0.23 | 0.29 | 0.41 | -0.14 | -0.27 | -0.46 |
| | 6-front axle | 0.18 | 0.32 | 0.38 | -0.15 | -0.29 | -0.44 |

speeds over the obstacles, the six accelerometers record maximum values of acceleration, in the three directions, as given in Table 3.

In the case of the road with a single obstacle**,** the simulation showed the following:

- The simulation allowed for determining the maximum speed of the truck, namely 11 km/h, while driving on a single obstacle road.
- Driving with a speed more than 10 km/h (for example, even at 11 km/h) on such a road category where there are no obstacles, does not lead to loss of lateral stability, but rather to obtain increased vertical accelerations, of approximately 2g. Such behaviour is due to the fully dynamic compression of suspension, reaching the travel limiter, which results in shocks transmitted to the vehicle chassis.
- Geometrical dimensions of obstacles, associated with a reduced driving speed, led to acceleration values that does not affect the cargo. For example, maximum acceleration values, while driving with 10 km/h were: 0.95g on a vertical plane, 0.52g on a lateral direction and 0.23g on a longitudinal plane.
- Driving on such road categories has led to higher values of roll angle, of approximately 3.5°, and to medium values of pitch angle, of approximately 1.85°. These values are slightly smaller as compared to the situation when the truck drives on a multiple obstacle road.One must take into account that the simulation was performed within conditions based on simplified assumptions (i.e. driving speed was predefined, constant and was instantly achieved; the braking system was not used, which is highly improbable in a real situation, no gear shifting at all etc.). Therefore, the validation of the simulation can be done only after conducting the experimental research. Still, while performing the experimental research, it should be taken into account the maximum recommended speed for such road category, to ensure safe driving conditions, according to the simulation.

*Multiple obstacles*

In the case of multiple obstacle road simulation, three constant driving speeds have been chosen: 3.5 km/h, 5.5 km/h and 7.5 km/h. In order to analyse results in case of passing over the multiple obstacle track, the data was obtained while driving with a constant speed of 7.5 km/h (the speed has been chosen arbitrarily, from the mentioned speed values used for simulation), as depicted in Figure 11. Passing over the speed of

**Table 4.** Maximum and minimum values of accelerations recorded in all six measuring points

| Speed [km/h] | Measuring point | Maximum values [g] | | | Minimum values [g] | | |
|---|---|---|---|---|---|---|---|
| | | X | Y | Z | X | Y | Z |
| 3.5 | 1 | 0.133 | 0.077 | 0.243 | -0.148 | -0.081 | -0.194 |
| | 2 | 0.123 | 0.077 | 0.309 | -0.143 | -0.081 | -0.327 |
| | 3 | 0.134 | 0.275 | 0.846 | -0.148 | -0.222 | -0.453 |
| | 4 | 0.124 | 0.275 | 0.768 | -0.180 | -0.221 | -0.624 |
| | 5 | 0.133 | 0.082 | 0.231 | -0.148 | -0.082 | -0.180 |
| | 6-front axle | 0.135 | 0.140 | 0.293 | -0.234 | -0.141 | -0.171 |
| 5.5 | 1 | 0.146 | 0.164 | 0.263 | -0.188 | -0.158 | -0.265 |
| | 2 | 0.153 | 0.166 | 0.331 | -0.171 | -0.157 | -0.296 |
| | 3 | 0.146 | 0.328 | 0.845 | -0.188 | -0.316 | -0.540 |
| | 4 | 0.154 | 0.330 | 0.811 | -0.171 | -0.316 | -0.492 |
| | 5 | 0.146 | 0.150 | 0.274 | -0.188 | -0.161 | -0.252 |
| | 6-front axle | 0.172 | 0.237 | 0.275 | -0.246 | -0.177 | -0.184 |
| 7.5 | 1 | 0.137 | 0.230 | 0.443 | -0.181 | -0.260 | -0.334 |
| | 2 | 0.121 | 0.232 | 0.365 | -0.184 | -0.258 | -0.457 |
| | 3 | 0.138 | 0.427 | 1.097 | -0.181 | -0.632 | -0.673 |
| | 4 | 0.132 | 0.467 | 0.963 | -0.183 | -0.630 | -0.731 |
| | 5 | 0.137 | 0.218 | 0.399 | -0.181 | -0.260 | -0.320 |
| | 6-front axle | 0.142 | 0.302 | 0.376 | -0.260 | -0.280 | -0.399 |

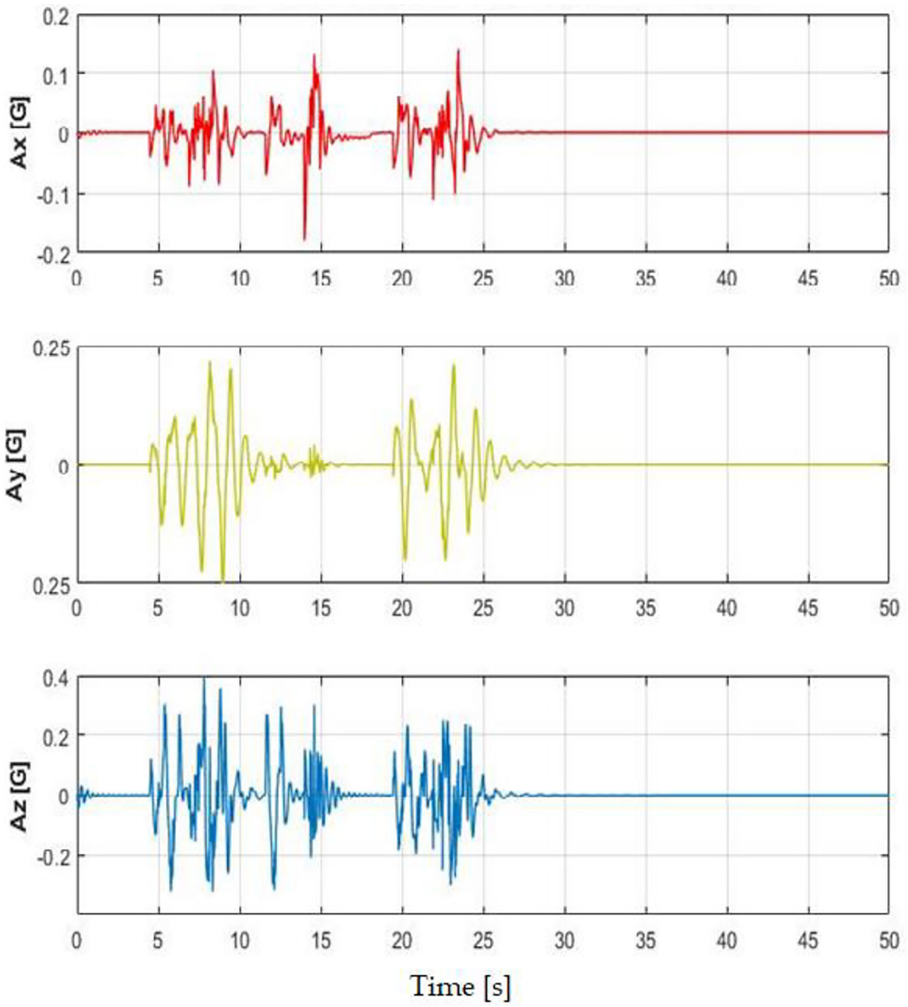


**Figure 11.** Time variation of accelerations measured by accelerometer number 5 while driving with a constant speed of 7.5 km/h

9 km/h, on such road category, has led to an amplified rolling movement [35] resulting in the loss of stability for the simulated truck.

Also, Figure 12 depicts the rolling and pitch angle of sprung mass time histories for a constant speed of 7.5 km/h. For the entire arbitrarily chosen constant driving speeds, while the truck passes over the obstacles, all six accelerometers recorded maximum values of accelerations, in three directions, as presented in Table 4.

- In case of the road with multiple obstacles, the simulation showed the following:
- The modelling – simulation software has some limitations regarding the maximum number of obstacles, but the three series generated in the model were adequate to obtain results.
- Simulation of the truck driving on multiple obstacles has highlighted prevalent lateral accelerations, which reached up to 0.7g while running with a constant speed of 7.5 km/h. Lateral accelerations were higher than the values obtained while running on multiple obstacles roads even though the speed was lower. The obstacles layout was decisive for the obtained values.
- For the same constant speed of 7.5 km/h, the maximum value of vertical acceleration was obtained, namely 1.1 $g$ in measuring point number three, at timestamp 7.87 s, meaning after passing over the first series of obstacles.
- This simulation allowed establishing the truck's limitations regarding lateral stability. As to be expected, the maximum value of roll angle was 4.58° and it was obtained while driving with a constant speed of 7.5 km/h and it decreased once the driving speed decreased. For example, the maximum roll angle was 3.48° for a constant speed of 5.5 km/h and 3.21° for a constant speed of 3.5 km/h.

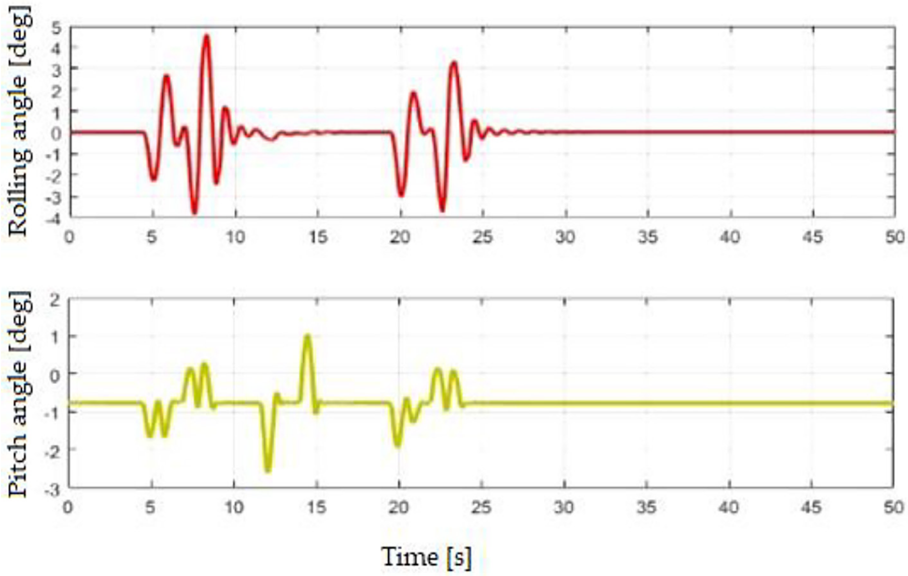


**Figure 12.** Time variation of rolling and pitch angle of the sprung mass

- Simulation allowed determining the maximum speed, meaning 9 km/h, so that the truck does not lose lateral stability. Over this value, an abnormal behaviour of the truck was observed, concerning its lateral stability.
- It can be concluded, by analysing maximum acceleration, that the values are within the normal range (according to [30]), which wouldn't lead to cargo damage.
- Acceleration values measured at the front axle, in the longitudinal direction, are higher than the values recorded in all the other measuring points in the longitudinal direction.
- It was analysed the compression rate of front axle suspension, while driving with a constant speed of 7.5 km/h. It was observed that when both wheels of an axle touch shifted obstacles, the elastic element of suspension coming first to pass the obstacle is compressed, while the one belonging to the other wheel is elongated. This was expectable considering the rigid axle.

## Experimental results

Military equipment is subjected to tests of vibrations which occur during transport and which are transmitted through the vehicle systems up to the container, the transport boxes and to the transported goods, based on standardised testing procedures, according to AECTP 400, method 401 from NATO STANAG 4370 [8]. The current subsection is divided into two parts: experimental results for a single obstacle and for multiple obstacles.

### *Single obstacle*

In the case of the single obstacle road, the maximum values of accelerations recorded in no. 1–5 (except at point no. 6 where the accelerometer signal was lost), were 1.315 g as given in Figure 13.

Regarding the experimental results obtained while driving on single obstacle roads, it can be mentioned:

- Maximum driving speed was below 10 km/h to avoid amplifying the rolling motion of the tested truck (Figure 13).
- While driving with 10 km/h, the maximum absolute value of acceleration was 1.315 g along $y$ axis and 1.02 $g$ along $z$ axis (specific to vertical acceleration).
- Compared to mechanical shocks which lasted between 2...20 ms, oscillations have been according to frequencies of 0.8 Hz–1.2 Hz, which are specific to suspension natural frequency [36–39].

### *Multiple obstacles*

Figure 14 presents details of maximum and minimum values of accelerations recorded in measuring point number five, for several driving speeds. In addition, Figure 15 shows the root mean square (RMS) values of acceleration for the multiple obstacle road, in the case of measuring point number five. Regarding the results obtained while driving on multiple obstacles road, it can be mentioned: Running on a multiple obstacle road led to prevalent values

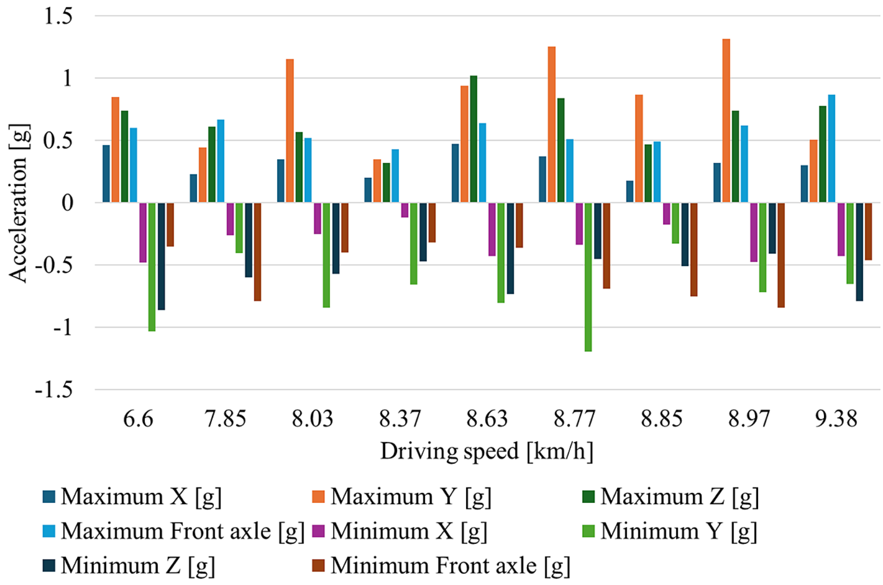


**Figure 13**. Maximum values of accelerations recorded in points no. 1–5 single obstacle road

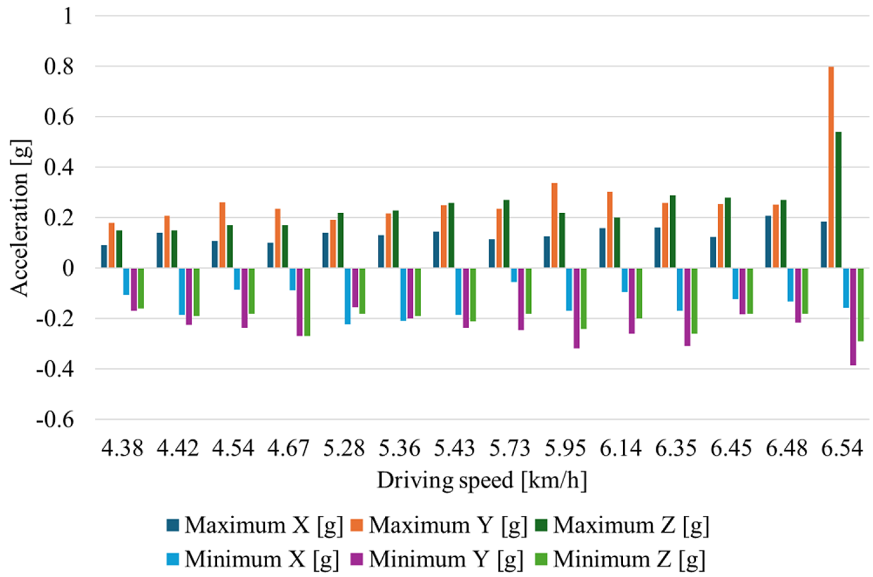


**Figure 14.** Maximum values of accelerations recorded in measuring point no. 5 for multiple obstacle road

of lateral accelerations which reached values up to 0.798 g (Figure 14). Analysing root mean square values of lateral accelerations, it can be concluded that the maximum value is around 0.1295 g, which does not affect the lateral stability of the truck, according to AECTP 400, method 401 from NATO STANAG 4370 [8] (Figure 15). Due to the low driving speed used to test the truck (between 3.84 km/h and 7.2 km/h), the suspension could return to its initial position after passing over obstacles and before reaching the next one (frequencies, close to the suspension natural frequency).

## DISCUSSION

The simulation research identified 11 km/h as the maximum safe speed for a truck driving on a single obstacle road. Speeds above 10 km/h, do not compromise lateral stability but result in increased vertical accelerations (approximately 2 g) due to full suspension compression. At 10 km/h, the maximum accelerations recorded were: 0.95 g (vertical), 0.52 g (lateral) and 0.23 g (longitudinal) which are within safe limits for cargo integrity. In the case of multiple obstacles road lateral accelerations reached up to 0.7 g at a constant speed

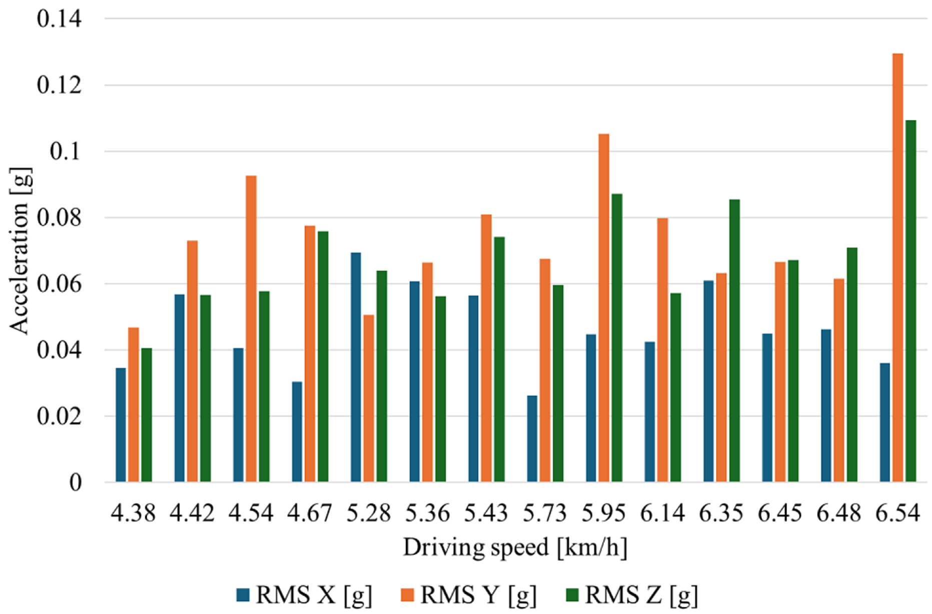


**Figure 15.** Root mean square values of acceleration in measuring point no. 5 for multiple obstacles road

of 7.5 km/h, however vertical acceleration peaked at 1.1g after passing the first series of obstacles. The maximum safe speed to avoid lateral instability was determined to be 9 km/h. Speeds above this value resulted in mentioned lateral instability. However, it also should be taken into account that the simulation was based on simplified conditions (constant speed, no braking, no gear shifting).

In the experimental studies with the single obstacle the maximum driving speed was kept below 10 km/h to prevent excessive roll motion. At 10 km/h, the maximum recorded accelerations were: 1.315 g (lateral), 1.02 g (vertical). In the case of multiple obstacles road lateral accelerations reached up to 0.798 g and the maximum RMS value of lateral accelerations was 0.1295 g, which is within the stability limits [8].

## CONCLUSIONS

The presented differences of the values of acceleration recorded along the three axes during simulation are due to TruckSim's sampling rate limitation (upper limit is 40 Hz, relative to the 2000 Hz frequency used during experimental research). Therefore, it can be concluded that the model has sufficient precision of simulating the truck while driving on a road with single or multiple obstacles, in order to analyse vibrations. In addition, simulation tests give the opportunity to identify indications that are burdened with large errors and eliminate them from the series of measurements. The tested vehicle's suspension system is effective in mitigating the impact of single and multiple obstacles on the road. It can effectively maintain vehicle stability at low speeds. Still, present research was conducted on an older version of military truck belonging to the Romanian army, which was equipped with leaf spring suspension and hydraulic dampers on the front wheels and leaf suspensions for the rear ones. A better option is the use of modern hydropneumatic models of suspensions, which ensures a combination of hydraulic fluid and gas (usually nitrogen) which allows for better absorption of shocks and bumps. Also, it offers an easier way to fine-tune for specific performance requirements, offering better adaptability to various driving conditions. Yet again, hydropneumatic suspensions can enhance vehicle stability, especially in off-road conditions, by providing consistent and adjustable damping forces. The results highlight the importance of maintaining speed limits, understanding vehicle dynamics and suspension behavior, and validating simulation results through experimental testing to ensure vehicle stability and cargo safety under various road conditions. Additionally, the results of the study allow establishing truck limitations regarding lateral stability. Overall, the obtained results of the research could be used further for improving the design and analysis of the performance of suspension in vehicles operating on single and multiple obstacle roads.

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