Chapter 3

# Analysis of Highway Acceleration in Regard to Cargo Security

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Additional information is available at the end of the chapter

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**Abstract**

Cargo security during road transportation particularly presents a current topic in the context of transport safety. One of the key factors influencing the magnitude of impact (acceleration coefficients) during transportation is the quality of the road networks. Acceleration coefficient values directly affect the rate of inertia forces influencing the cargo. Given that the inertia force magnitudes (acceleration coefficients) are not known prior to commencing the actual transport, acceleration coefficient values known from regulations or otherwise (for example, empirically) certain established values must be used. Values of acceleration coefficients were established in EN 12195–1, a regulation typically used within the European Union. This chapter covers the approaches of this standard and provides comparison of acceleration coefficients established through regulations with those measured. Data (coefficient acceleration) from both highway transport and unpaved roads (in off-road conditions) were measured and statistically processed for comparison purposes. The transportation model presented subsequently demonstrates differences in the magnitude of inertia forces using three sets of data—acceleration coefficients obtained from the standard, from highway transport, and from off-road transport. At the same time, these secured cargoes were set into an insufficient context, where unsuitable or insufficient security of the cargo represents one of the significant risks in the occurrence of an accident.

**Keywords:** transportation, cargo security, transport model, acceleration coefficient, inertial force, accident rate

## 1. Introduction

The growing demand for cargo transport is related to the increase of transport performance in road transport. This is evident not only in Europe but also in the Czech Republic, which is a transit state for road haulers.

In 2015 in the Czech Republic, 438,906,000 tonnes of cargo was totally transported. Compared to 2010, it is more than a 23.3% increase (355,911,000 tonnes) [1].

Studies and statistics show that in the last decade, the gross weight of goods in containers handled in European ports increased by 30%. Many roads are already overloaded, because over three quarters of the total cargo volume (76.4%) in Europe is carried on roads [2]. The road infrastructure, which is highly loaded and often overloaded, is increasingly damaged, and annual maintenance often fails to provide the required quality of road infrastructure.

According to the data from the Road Transport Services Center (established by the Ministry of Transport of the Czech Republic), over half of vehicles are overloaded during weight checks. The number of weight checks surpasses 2000 per year [3].

Road quality (among others) directly affects the inertia force effect of cargo during transport. Generally, for a damaged road that has considerable unevenness (holes, potholes, etc.), higher values of acceleration coefficients can be assumed, which directly affects the value of inertia forces.

Load securing, also known as cargo securing, is the securing of cargo for transportation. According to the European Commission Transportation Department, it has been estimated that up to 25% of accidents involving trucks can be attributed to inadequate cargo securing [4].

From the point of view of the safety of cargo transport, one must consider the value of assumed inertia forces affecting the cargo and secure (fasten) the cargo with appropriate fastening means that correspond to the assumed inertia forces. The estimated quarter of traffic accidents, where an incorrect or insufficient load attachment is identified as a cause, are usually a combination of greater than the expected inertia forces and inappropriate attachment.

Determining the magnitude of the inertia for transport is possible using accelerometers and the appropriate calculation (e.g., using the relevant European standards). However, the size of the inertial forces must be known in advance and a suitable and sufficient method of fixing the cargo should be chosen accordingly. For this purpose, the empirically determined and statistically evaluated acceleration coefficients are used, which are part of EN 12195-1—Safety—Part 1: Calculation of securing forces, valid in the European Union.

The shortage is mainly at statistical processing, which is "averaged" for Europe. However, it is evident that the quality of the transport infrastructure and possibly also the quality of the various categories of roads differ significantly, not only when comparing several European countries but also within a given country. The Czech Republic is not an exception. Differences can be identified between repaired (upgraded) and older (not repaired) sections of the same road.

The aim of the chapter using the case study is to point out the deficiencies in the use of the abovementioned empirically determined and statistically processed values of acceleration coefficients. This thesis will subsequently be demonstrated within the framework of the performed transport model.

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## 2. Acceleration and its impact on cargo securing

Acceleration, as well as vibrations, may adversely affect cargo transport. This is especially the case when, for some reason, cargo is detached and subsequently damaged. As a result of the detaching of the cargo, other technical elements such as fasteners (e.g., straps), transport means (e.g., pallets, containers), or the means of transport itself may be damaged. In some cases, injuries to the operator may occur. Such cases occur mainly in international traffic, where the goods are transported over long distances by more modes of transport (within multimodal transport).

A relatively self-contained area is also an incorrectly located center of gravity of the handling unit due to inappropriate loading—whether it is a container unit, a unit using an exchangeable extension, or a balancing of its own means of transport. In such cases, the appropriate handling and transport unit may be removed from the transport—most often in the case of air transport, where the requirement to place the center of gravity of handling and transport unit (container unit) is most strict.

A bigger problem, which may be caused by incorrect placement of the center of gravity of the handling and transport unit, is a particular problem during handling and transport in the case of container units designed for multimodal transport. In such cases, such a handling and transport unit (container) may not meet the requirements of the relevant international standard (ISO) [5], which states the basic load distribution condition in standardized ISO container type 1 (see **Figure 1**).

A simple condition relating to 60% of the weight of the load in the half of the container unit can be transformed, using the balance on the lever into the maximum deviation of the center of gravity of the container unit ±10% in the x-axis (see **Figure 1**). **Figure 1** shows a situation where the center of gravity in the x-axis is moved by the maximum possible deviation to the left, i.e., the position of the center of gravity of the x-axis container unit is 10%.

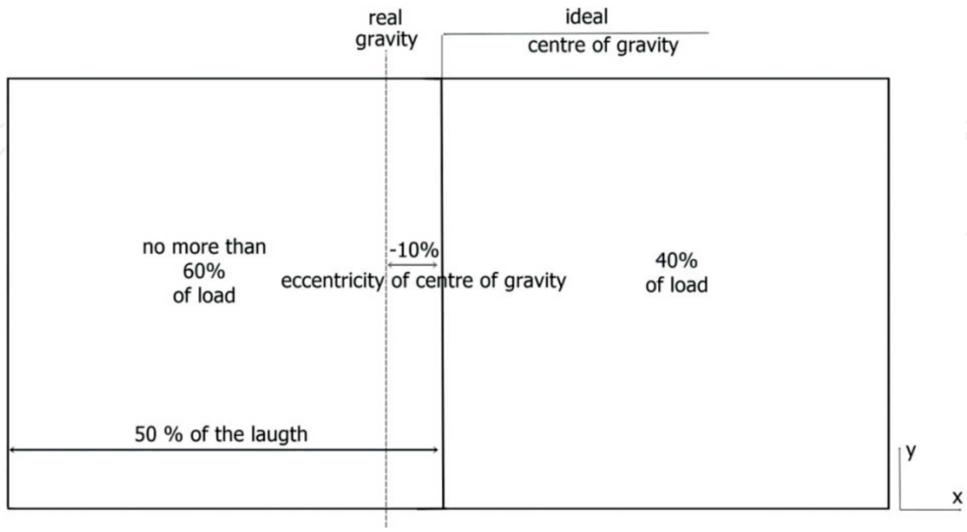


**Figure 1.** Load distribution in ISO containers. Source: modified from Refs. [5, 6].

The x-axis is the longitudinal axis according to the standard marking in relation to the movement of the means of transport (see **Figure 2**).

It is worth mentioning that much software is designed to load containers. The software contains conditions that ensure the permissible location of the center of gravity of the container unit and is usually supplemented by the same condition for the y-axis (according to the standard marking of the axis perpendicular to the x-axis, i.e., the axis of movement of the means of transport). With sensitive loads, this condition can be tightened and is available with certain software products.

Simply said, if the cargo of the handling and transport unit (or the direct means of transport) is properly distributed and secured, it is assumed that the abovementioned negatives (risks) will not occur. Obviously, there may be unexpected situations when cargo can be detached during handling, especially loading, unloading, and shipping.

The issue will be examined from the point of view of the possible cause of a traffic accident due to insufficient or improper attachment of the cargo at handling and transport unit. Cases where an accident or similar unexpected situation occurs will not be further investigated.

Determining the magnitude of the inertial forces stems from Newton's second law of motion, which defines the force as the product of mass—in this case, the mass of the load (m) and the acceleration (a). For the purposes of the transport model, the magnitude of the inertia force at given axis will be relevant, not its vector expression (direction):

$$F = m \cdot a \tag{1}$$

Acceleration can be defined as corresponding acceleration coefficient (i.e., for the respective x-, y-, or z-axis) that is dimensionless in the context of the values of acceleration coefficients used, which are determined (empirically measured) normatively (see EN 12195-1), multiplied by gravitational acceleration (g):

$$a = c_{x,y,z} \cdot g \tag{2}$$

Although gravity acceleration ranges from 9780 $ms^{-2}$ on the equator to 9832 $ms^{-2}$, which corresponds to the Earth's pole [8], for the needs of multimodal transport, logistics and

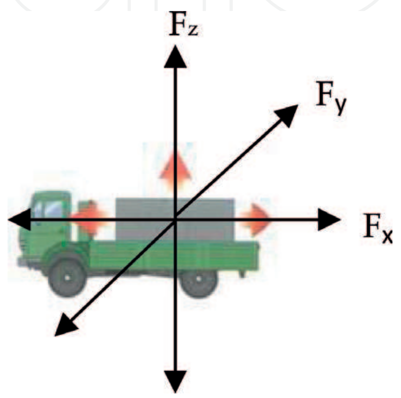


**Figure 2.** Inertia forces in individual axes. Source: modified from Sdruzeni ridicu [7].

transport generally use a rounded value of 10 $ms^{-2}$. Such accuracy of input data is not relevant in practice, and the advantage of rounding the gravitational acceleration is that the slightly higher value of the gravitational acceleration ensures a slightly higher value of the resulting inertial force. In the context of the above, the requirement for attachment is stricter, and from the point of view of the liability for damage, those responsible for the loading are protected by a hypothetical "reserve" given by the "stricter" load-bearing requirement.

After verification of the correct cargo attachment, inertia forces at all three axes (x, y, z) are identified. Their values are determined by their relation to the attachment method. For the purposes of this chapter, attachment methods using fastening straps will be further discussed, which are among the most used methods of fixing in road transport, especially for standardized pallet units.

For determining the value of inertia forces, the appropriate formulas (e.g., using the EN 12195–1) serve that best consider the abovementioned facts, i.e., attachment method and attachment means used. The use of fastening straps—the most commonly used attachment method—is further examined, the method of gripping the handling and transport unit (pallet unit). In such cases, EN 12195-1 identifies the formula for calculating only inertia forces in the x-axis ($F_x$), longitudinal force actuated by the load, and in the y-axis ($F_y$), transverse force actuated by the load [9]:

$$F_x = \frac{(c_x\text{-}\mu \cdot c_z) \cdot m \cdot g}{2n \cdot \mu \cdot \sin\alpha} \cdot f_s[N] \tag{3}$$

$$F_y = \frac{(c_y\text{-}\mu \cdot c_z) \cdot m \cdot g}{2n \cdot \mu \cdot \sin\alpha} \cdot f_s[N] \tag{4}$$

where $c_x$, $c_y$, and $c_z$ are acceleration coefficients in individual axes, μ is the friction factor, m is the mass of the load, g is the gravitational acceleration, $f_s$ represents the safety factor and the number of fastening straps, and finally, the angle $\alpha$ which holds the strap to the floor (horizontal plane).

This calculation can be performed using normative values of acceleration coefficients and friction factors. The accuracy and usability of the normatively determined values of the acceleration coefficients are discussed within the chapter. In the case of friction factor, some differences (inaccuracies) caused by the use of other materials may occur. It is most advantageous to use the friction factor directly from the manufacturer. This is commonly stated, especially in the case of nonslip coating surfaces.

The value of inertia force in z-axis ($F_z$)—vertical force actuated by the load—is not considered because it is sufficiently assumed to be less than at least one of the above inertia ($F_x$ or $F_y$). Consequently, the fulfillment of the condition is assumed:

$$(F_z \leq F_x) \vee (F_z \leq F_y) \tag{5}$$

It is clear from formulas (3) and (4) that the standard is working with a certain degree of abstraction, which is not only due to the absence of calculation of the value of inertia force in z-axis ($F_z$) but also due to other assumptions. For these reasons, the authors included the safety factor ($f_s$), which "artificially" increases the value of the resulting inertia forces (for the x- or y-axes) by 10 and 25%, respectively. The following text assumes $f_s$ = 1.25. The inclusion of a safety factor in the calculation results in the offsetting of the above abstraction rate and ensures the practical use of the calculation, while it also ensures its relative simplicity.

In practice, software products are used for simplicity, which usually speeds up the determination of inertia forces. However, the basis of calculation and input data is identical to the above-described "manual" approach. Thus software products will no longer be considered, and emphasis will be centered on input data (accelerator coefficient values) and calculation methodology.

The chapter will also focus on input values of acceleration coefficients. Normally, set values of these coefficients are characterized by several shortcomings. The first is their "averaging," i.e., the empirically determined values are statistically evaluated, and the exact method of their determination is not given in EN 12195-1. It can only be assumed that the resulting value of individual acceleration coefficients was based on the mean values that were increased by the "safety factor" analogue, which should include a high rate of abstraction in determining values and, above all, allow their practical use.

In particular, the values of acceleration coefficients do not consider the extreme fluctuations of the individual acceleration coefficients in the transport. To rely on a hypothetical basal vector (the highest empirically mentioned values of the acceleration coefficients in all three axes) would certainly not be effective. However, it should be considered under greater observation. The measurements made from empirical analyses (see below in Chapters 4 and 5) show that, in some cases, especially in roads in poor or bad technical conditions, extreme fluctuations pose a big problem.

Even double and higher rates of normatively determined values of acceleration coefficients are not an exception, and the data found that they represent more than 0.67% of all values, even in the case of the highway. The situation on lower class roads can be expected to be even worse, and the occurrence of extreme fluctuations is more likely.

Another lack of normative values of acceleration coefficients, which to a certain extent is related to the previous, is the non-consideration of infrastructure type (quality). This can be demonstrated (ad absurdum) to compare inertia forces during transport by road (or first-class roads) and off-road transportation (see **Figure 3**).

At the first sight, there is a visible difference between the central part of the chart, which represents the ride on off-roads, and the marginal ones that represent the highway from Brno to Vyškov and, after field training, back from Vyškov to Brno.

Off-road transport has very limited impact upon normal commercial transport and is only interesting for integrated rescue systems or the army. However, based on the data (see below), one may assume a graduation of the magnitude of the acceleration coefficients in relation to the roads of given classes, especially on their quality. The eventual inclusion of off-road conditions can only serve as a logical addition to extremes, identifying both the best considered roads (highways) and the worst alternative (off-road).

Specific road quality of a given class, of course, must be generalized, but the output would offer a set of acceleration coefficients for a given type of infrastructure (road). Such an approach would ensure an effective consolidation concept, i.e., the use of fastening methods

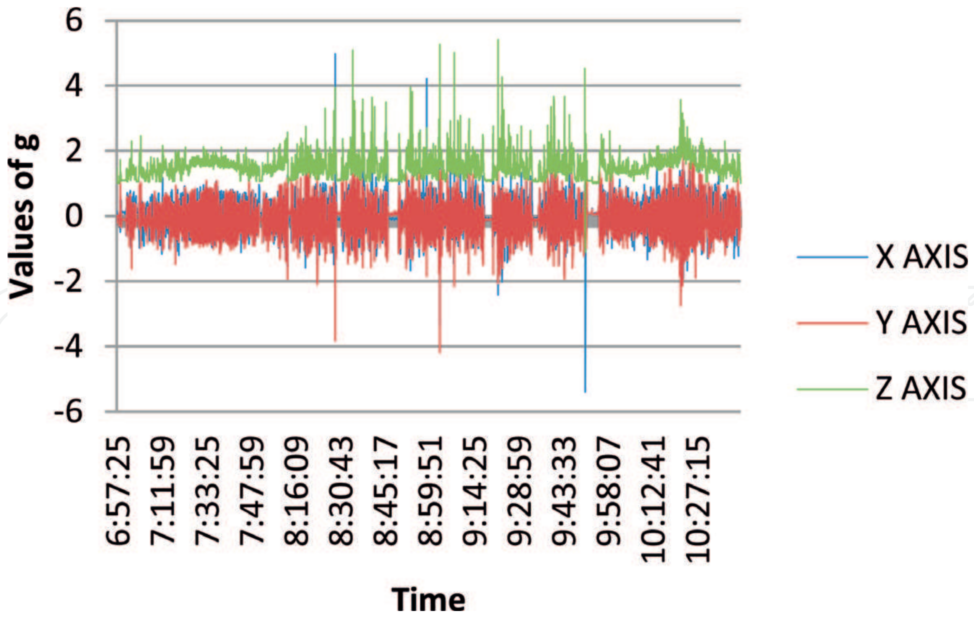


**Figure 3.** Values of acceleration coefficients (Brno–Vyškov and return).

with such load-bearing capacity of the fastener that it would provide sufficient protection of cargo carried against the inertial forces in all three axes. On the other hand, there would be no second extreme, and it is an "over-dimensioning" fixation according to the philosophy of Just in Case.

Just in Case's philosophy is known primarily from the history of inventory theory [10], i.e., maintaining inventory in every case represents the opposite of Just in Time philosophy. This approach can easily be demonstrated in the case of the use of fastening straps, where the load-carrying capacity of the entire fastening system (more straps) can be measured in a variable manner by a suitable combination of the binding capacity of individual straps and their number. The result would be a use of the optimal number of fastening straps to provide optimal protection against inertial forces in handling and transporting the cargo.

This solution offers the optimal proportion between sufficient fastening to avoid damage to cargo or using other technical means and the number of fastening straps, not only their number but also the time required for their placement and tension, including subsequent removal and reverse logistics.

## 3. Highways in the Czech Republic and accident rates

In the Czech Republic, there are a total of 55,737.5 km of roads and highways (year 2015). This number has remained virtually unchanged since 2010 (55,751.9 km). Highways represent a relatively small share (only 1.4% from a total length of 776.0 km). Roads of "very good" quality also include the Class I roads, which include expressways. Their total length in 2015 was 6244.9 km. The percentage of highways and Class I roads in the total road network is nearly 12.6%.

However, this category does not include local roads owned by individual municipalities, which are often in a worse technical condition. The total length of local roads is 74,919.0 km. If we compare the length of highways and Class I roads to total length of roads and local roads (130,656.5 km), their share would be very small: less than 0.6% of highways and 5.4% of combined highways and Class I roads [1].

Due to the assumed lower occurrence of extreme variations (values) of acceleration coefficients on highways and Class I roads, the normative values given in EN 12195-1 can be used for these purposes. However, in the remaining 98.6%, respectively, 87.4% of cases may vary and the assumed values of the coefficients of acceleration (or resulting inertial forces) may be higher. Therefore, there is a real risk that cargo will not be appropriately (sufficiently) attached to the vehicle for these purposes. If we include local communications, the situation would dramatically worsen.

Compared to the European Union, the Czech Republic is considered relatively average in road network length, including its length of highways (see Transport Yearbook 2015). The comparison of the Czech Republic with neighboring states is interesting, as some disproportions can be identified here; for example, Poland is significantly larger, both in terms of size and number of inhabitants, yet has only roughly twice the length of highways compared to the Czech Republic. Germany, on the other hand, has a 17 times longer length of highways than the Czech Republic. Austria has more than double and Slovakia only half the length of highways in the Czech Republic.

Over the past 8 years (data available only until 2013), there is a different trend in the volume of road freight transport in the European Union. In the Czech Republic, the increase in tonne-kilometers transported exceeds 26.3% (an increase from 43,447 tkm to 54,894 tkm from 2005 to 2013). For neighboring countries and certain other countries of the European Union, the situation is often different for the same period examined. Poland recorded one of the largest increases in the volume of road freight transport in the European Union, by more than 121.4%. Germany is relatively stagnant, with a slight decrease by 1.4% over the period under examination. Austria recorded a larger decrease of more than 34.6%, and finally, the situation is similar in Slovakia to that in the Czech Republic, and the Slovak volume of road freight transport grew by almost 33.6% [1].

Accidents in road transport are a large long-term problem. In the Czech Republic, despite several preventive measures, the number of accidents failed to fall. Such measures include a suitable setup of the transport system, better information for drivers, as well as measures to reduce the risk of injury or death by road users—especially of a technical nature for vehicles and transport infrastructure.

The total number of road traffic accidents in the Czech Republic in 2005 was 25,239. In 2010, it was only 19,676; however, in 2015, it rose again to 21,561 [1, 11–13].

This increase in the number of road traffic accidents is caused by the steady increase of vehicles (see **Table 1**) registered in the Czech Republic, a comparable situation as in the rest of Europe.

It is clear from **Table 1** that, although there was a slight increase in the number of accidents between 2010 and 2015 (less than 9.6%), the increase in the number of vehicles registered in the

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Czech Republic has become much more significant in both most important segments (for passenger cars and trucks). This increase was observed between 2010 and 2015, when the number of accidents increased by almost 13.8% for passenger cars and nearly 10.6% for trucks. Compared with 2000 (2000–2015), the increase is very significant: almost 49% for passenger cars and nearly 138% for trucks.

A positive trend is in the number of people killed within 30 days of the accident, which has steadily declined since 2000 (with few exceptions in 2002, 2007, and 2014). In 2015, it dropped to half its level of 2000 (see **Table 2**).

In the case of the number of injured, there was also a significant decrease between 2000 and 2015 (almost 16.9%), yet the trend has increased in recent years. Between 2010 and 2015, this statistic grew by nearly 10.6%.

A certain lack of statistics at the national level is caused by the absence of a distinction between technical causes of accidents and specific types of technical defects. Section 6.2.1 of each transport yearbook classifies road traffic accidents according to location and type, but the technical cause is not shown. These statistics are recorded by certain traffic haulers in their information systems. Unlike aggregated statistical data from the Czech Republic, it is generally not publicly available and thus serves only to manage the operation and vehicle fleet of the relevant entity (hauler) [14].

In other words, if the carrier fails to publicize its own data collection, it is not possible to determine from official statistics how many times a road traffic accident occurred due to improperly or insufficiently secured cargo.

| Number/year | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|
| Road traffic accidents | 25,445 | 25,239 | 19,676 | 21,561 |
| Passenger cars* | 3,438,870 | 3,958,708 | 4,496,232 | 5,115,316 |
| Trucks* | 275,617 | 415,101 | 584,921 | 646,792 |

*Vehicles registered in the Czech Republic.
Source: Refs. [1, 11–13].

**Table 1.** The development of road traffic accidents in the Czech Republic and the number of vehicles in the selected segment.

| Number/year | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|
| Killed* | 1486 | 1286 | 802 | 738 |
| Injured | 32,439 | 32,211 | 24,384 | 26,966 |

*Number of those killed in road traffic accidents within 30 days from the date of the accident.
Source: Refs. [1, 11–13].

**Table 2.** Number of people killed or injured in road traffic accidents in the Czech Republic.

## 4. Statistics: evaluation of acceleration coefficients

The basic approach to the statistical evaluation of measured data is a demonstration of extremes—values of acceleration coefficients on the highway and their comparison with values measured on unpaved roads (off-road). Comparison with the normative values of the acceleration coefficients is also part of the comparison.

The basis for statistical evaluation is the graph in **Figure 3**, which illustrates the situation where a group of drivers is transported to a training location on an unpaved road (off-road) and then returns. The chart in **Figure 3** contains raw data, which was subsequently cleaned up by a part of the transport at the city and breaks between the beginning of training rides on unpaved roads (off-road) and between drivers who took part in those trainings. In total, there were six drivers, and one of them provided transport to training from Brno to Vyškov and return.

The aim of the evaluation is a statistical analysis of the measured acceleration coefficients, to find point and interval estimates of the parameters of the partial files and to compare the parameter estimates using statistical tests. The acceleration coefficients for individual axes from the set of measurements taken on the highway and unpaved road (off-road) are compared.

Statistical analysis was performed by the test of normality, which was graphically verified using a Q-Q plot [15]. Normality testing was performed using predetermined skewness and kurtosis coefficients [16]. These tests showed slight deviations from normality, especially during the testing of skewness of distribution; however, the graphic analysis failed to reveal significant deviations from normality. Theoretical quantiles and the corresponding empirical quantiles were approximately in a straight line. For illustration, **Figures 4** and **5** show the Q-Q plots for the given training rides on the unpaved road (off-road) and the measured acceleration coefficients in the x- and y-axes [17].

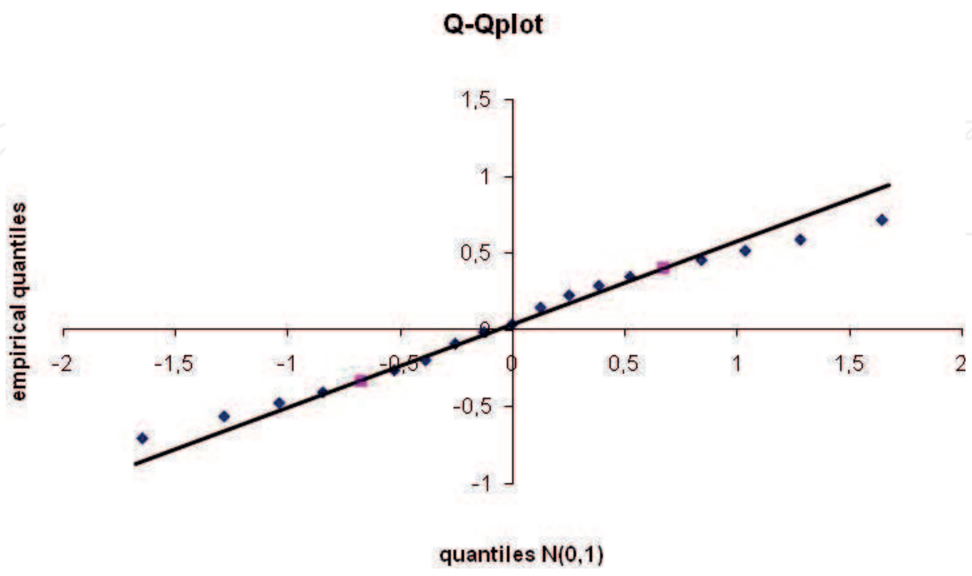


**Figure 4.** Q-Q plot: unpaved road (off-road)—acceleration coefficients at coordinate x. Source: Vlkovsky et al. [17].

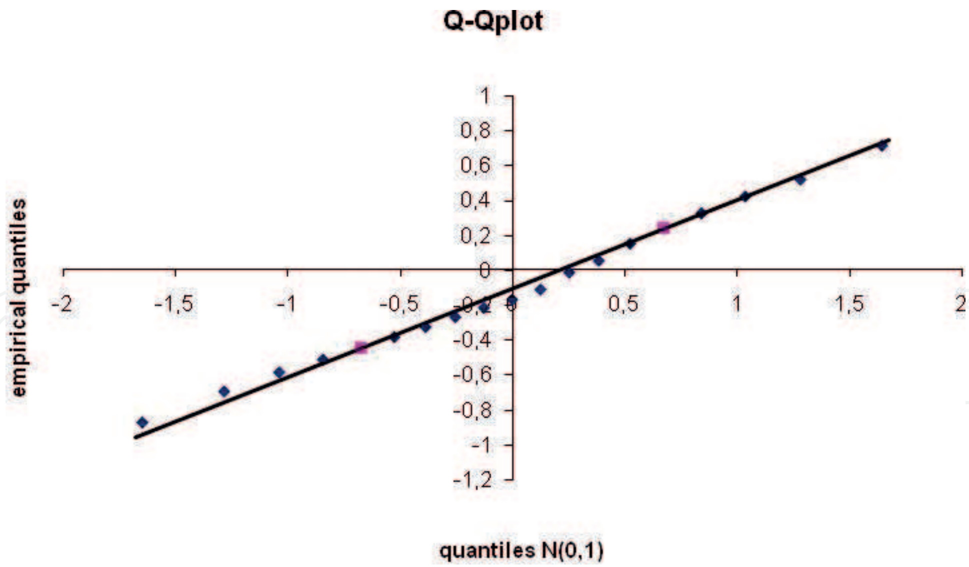


**Figure 5.** Q-Q plot: unpaved road (off-road)—acceleration coefficients at coordinate y. Source: Vlkovsky et al. [17].

Due to the large scale of compiled sets (more than 5000 data in each set) asymptotic confidence intervals are used, and asymptotic statistical tests are based upon assumptions of asymptotic normality of the observed characteristics [15, 16].

Data is the averaged output of the four measuring devices (accelerometers), and the values are compared with the basal variation of the acceleration coefficients given by the standard [9]:

$$v_n = (0.8, 0.6, 1.0). \quad (6)$$

The measurement for the z-axis started at 1 g, i.e., the value of 1 g of the basal variant corresponds to 2 g on the measuring device. From the measured data, two statistical files were created, which were cleaned by a ride through the city and the vehicle's stop time due to the replacement of the drivers.

The first set was measured on the highway (index 1), and its range is $n_1 = 6148$. The second set was measured on unpaved communication (index 2), and its range is $n_2 = 5257$. For both sets, the basic characteristics of the mean and sample standard deviation were then determined as the expected value $\mu$ and standard deviation $\sigma$. In addition, for individual axes the number of values was set that exceeded the value given by the standard. The relative frequency of numbers was an estimate of parameter $\theta$, which indicated the probability of exceeding norms. Estimated characteristics matched with both the first set of data obtained by measuring on the highway by index 1 and for the second set of data obtained by measurement on unpaved road (off-road) by index 2. The estimates were supplemented with 95% confidence intervals for each parameter [17].

The comparison of both data files (file 1 and file 2) was performed by comparing the standard deviations $\sigma_1$ and $\sigma_2$, then comparing the mean values $\mu_1$ and $\mu_2$, and comparing the probabilities $\theta_1$ and $\theta_2$. Comparisons are made for each axis (x, y, z).

| Confidence interval for | Acceleration measurement in the axes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | x | | | y | | | z | | |
| | PE | LB | UB | PE | LB | UB | PE | LB | UB |
| $\sigma_1/\sigma_2$ | 0.904* | 0.881 | 0.928 | 0.914* | 0.891 | 0.938 | 0.778* | 0.758 | 0.799 |
| $\mu_1$-$\mu_2$ | −0.008 | −0.0251 | 0.0097 | −0.013 | −0.0305 | 0.0050 | 0.008 | −0.0028 | 0.0188 |
| $\theta_1$-$\theta_2$ | −0.0141* | −0.0228 | −0.0054 | - 0.0157* | −0.0307 | −0.0007 | −0.0156* | −0.0231 | −0.0081 |

*Means significant difference between parameters of the first and the second dataset at a 5% significance level.
PE—parameter estimation; LB—lower boundary of 95% confidence interval; and UB—upper boundary of 95% confidence interval.
Source: Vlkovsky et al. [17].

**Table 3.** Statistical tests of equality.

Using these confidence intervals, statistical tests were then performed at the significance level of 5% (significance level) to compare individual pairs of the parameters. Calculated confidential intervals were based on the methodology described in [15, 16].

It can be seen from **Table 3** that the mean values of the acceleration coefficients in each of the axes (x, y, z) between sets are obtained on the highway and unpaved road (off-road). Unpaved roads (off-road) are statistically significant at 5% of the significance level. On the other hand, the variability of the comparison sets is statistically significant in each axis. The variability of acceleration coefficient values measured on the highway is significantly statistically lower than the variability measured on unpaved roads (off-road). Also, the probability values of exceeding the norm in each of the axes are statistically significant. Probability of exceedance is higher (as expected) on unpaved roads (off-road) [17].

## 5. Transport model

The transport model is designed to illustrate the differences between the evaluated files (see chapter 4) and to demonstrate the effect of the extreme values of the acceleration coefficients on the resulting inertial forces ($F_{x,y}$) that affect the cargo during transport.

The basis of the designed model is the creation of basal variants for both measured sets—the values of the acceleration coefficients detected on the highway and on unpaved roads (in off-road). Basal variants are created as the average of the three largest (in absolute value) fluctuations in each of the axes within a given set. Input values are summarized in **Table 4**, including the time at which the fluctuations occurred. Values in z-axis are cleared by 1 g in terms of displacement of the measurement axis, i.e., the value of gravitational acceleration (1 g).

Based on the highest values in **Table 4** and their average, basal variations are created for both data files ($n_1$, $n_2$). Shock direction—the sign is not considered; the value of the acceleration

| | Acceleration measurement in the axes-extremes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | x | | | y | | | z | | |
| Time($n_1$) | 10:22:07 | 10:22:44 | 10:23:01 | 10:22:08 | 10:22:12 | 10:23:01 | 10:22:07 | 10:22:08 | 10:22:44 |
| Value ($n_1$) | −2.0900 | −1.7225 | −1.9075 | −2.7425 | −2.3675 | 2.2650 | 2.3725 | 2.5650 | 2.1625 |
| Time($n_2$) | 8:29:14 | 8:59:07 | 9:51:01 | 8:29:14 | 8:35:01 | 9:03:27 | 8:35:01 | 9:03:27 | 9:22:36 |
| Value ($n_2$) | 4.9675 | 4.2175 | −5.4000 | −3.8200 | 2.3500 | −4.1825 | 4.1000 | 4.2700 | 4.4225 |

**Table 4.** Input values of basal variants.

coefficient is used, i.e., all values in **Table 4** are taken at absolute value. The resulting basal variants are:

$$v_1 = (1.9067, 2.4583, 2.3667). \quad (7)$$

$$v_2 = (4.8617, 3.4508, 4.2642). \quad (8)$$

The model is created under the following assumptions:

- the cargo is transported (attached) to a Tatra T-810;
- the cargo consists of a model pallet unit, which has a height of 1600 mm and is designed using a standard EUR pallet 1200 × 800 mm;
- the cargo on the pallet unit is fixed by default use of shrink film, and the fastening method is not the subject of the model;
- cargo weight of the pallet unit is 500 kg;
- the pallet unit is fastened with commonly available tie-down straps; the subject of the model does not determine the number or type of tie straps;
- the pallet unit is located longitudinally in relation to the direction of movement of the vehicle (x-axis);
- the source of data is created by basal variants (see above), and the normative values of the acceleration coefficients are given by EN 12195-1; and
- the formula and other necessary input data from EN 12195–1 are used for the calculation.

The model pallet unit and the method of its attachment are shown in **Figure 6**, from which it is possible to determine the angle $\alpha$ required to determine the magnitude of inertia forces.

From **Figure 6**, it is possible to determine the angle $\alpha$ from the known width of the vehicle's cargo space (2506 mm) and parameters of pallet unit (1200 × 800 × 1600 mm). The distance of the pallet unit heel to the anchor point (k) is then:

$$(2506 - 800)/2 = 853 \text{ mm}. \quad (9)$$

Using the trigonometry function, tangent can be calculated angle $\alpha$ with the height of pallet unit (v) and the distance of pallet heel from anchoring point (k):

$$tg\alpha = v/k \tag{10}$$

after using values:

$$tg\alpha = 1600/853 \tag{11}$$

$$\alpha = 61.94^{\circ} \tag{12}$$

The input values of the model for fitting into formulas (3) and (4) are shown in **Table 5**. For clarity, the magnitude of the inertia forces in the x- and y-axes will be examined. The $F_z$ value is

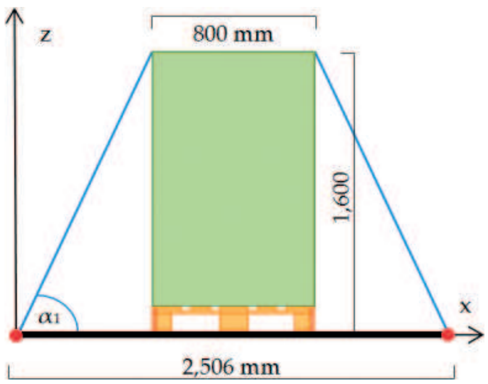


**Figure 6.** Method of fixing the model pallet unit. Source: Vlkovsky et al. [18].

| Variable | Value | | | Unit | Note |
|---|---|---|---|---|---|
| | Norm | Highway | Off-road | | |
| $F_{nx,y}$ | ? | — | — | N | Inertial force – norm |
| $F_{1x,y}$ | — | ? | — | N | Inertial force – highway |
| $F_{2x,y}$ | — | — | ? | N | Inertial force – off-road |
| $c_x$ | 0.8000 | 1.9067 | 4.8617 | — | Coefficient of acceleration (x) |
| $c_y$ | 0.6000 | 2.4583 | 3.4508 | — | Coefficient of acceleration (y) |
| $c_z$ | 1.0000 | 2.3667 | 4.2642 | — | Coefficient of acceleration (z) |
| $\mu$ | 0.4 | 0.4 | 0.4 | — | Coefficient of friction |
| m | 500 | 500 | 500 | kg | Mass of cargo |
| g | 9.81 | 9.81 | 9.81 | $ms^{-2}$ | Gravitational acceleration |
| $f_s$ | 1.25 | 1.25 | 1.25 | — | Safety factor |
| n | 1 | 1 | 1 | pc | Number of lashing straps |
| $\alpha$ | 61.94 | 61.94 | 61.94 | ° | Angel – among strap and floor |

**Table 5.** Input values of transport model.

not calculated because formula (5) is assumed to be valid. The value of the inertia forces in the x- and y-axes will be calculated using the normalized acceleration coefficients ($v_n$), basal variant 1 ($v_1$), and basal variant 2 ($v_2$).

The following designation is used to differentiate individual inertia forces with different input data:

- $F_{nx}$—inertial force in the x-axis using normatively determined acceleration coefficients ($v_n$)
- $F_{ny}$—inertial force in the y-axis using normatively determined acceleration coefficients ($v_n$)
- $F_{1x}$—inertial force in the x-axis using basal variant 1 ($v_1$)
- $F_{1y}$—inertial force in the y-axis using basal variant 1 ($v_1$)
- $F_{2x}$—inertial force in the x-axis using basal variant 2 ($v_2$)
- $F_{2y}$—inertial force in the x-axis using basal variant 2 ($v_2$)

After using the three variants of input data into formulas (3) and (4), the results are shown for overview at **Table 6**.

As apparent from the results in **Table 6**, acceleration coefficients significantly affect the resulting inertia force influencing cargo (affecting the fastening strap within the transport model). When using acceleration coefficients stipulated as normative, the cargo "behaves" according to expectations, meaning that resulting inertia forces in the x- and y-axes are relatively small. Even with the inclusion of the safety factor, they do not correspond to as little as 5000 N, which basically corresponds to the cargo weight (500 kg).

| Forces, ratio | Value | Unit | Note |
|---|---|---|---|
| $F_{nx}$ (for $v_n$) | 3.474 | N | — |
| $F_{ny}$ (for $v_n$) | 1.737 | N | — |
| $F_{1x}$ (for $v_1$) | 8.338 | N | — |
| $F_{1y}$ (for $v_1$) | 13.128 | N | — |
| $F_{2x}$ (for $v_2$) | 27.410 | N | — |
| $F_{2y}$ (for $v_2$) | 15.156 | N | — |
| $F_{1x} : F_{nx}$ | 2.40 | — | Inertial ratio in the x-axis – norm:highway |
| $F_{2x} : F_{nx}$ | 7.89 | — | Inertial ratio in the x-axis – norm:off-road |
| $F_{2x} : F_{1x}$ | 3.29 | — | Inertial ratio in the x-axis – highway:off-road |
| $F_{1y} : F_{ny}$ | 7.56 | — | Inertial ratio in the y-axis – norm:highway |
| $F_{2y} : F_{ny}$ | 8.73 | — | Inertial ratio in the y-axis – norm:off-road |
| $F_{2y} : F_{1y}$ | 1.15 | — | Inertial ratio in the y-axis – highway:off-road |

**Table 6.** Values of inertial forces in x and y axes and their ratios.

| Forces | Value | Unit | Note |
|---|---|---|---|
| $F_{nx}$ | 3.474 | N | For normative values of $c_x$, $c_y$, and $c_z$ |
| $F_{ny}$ | 1.737 | N | For normative values of $c_x$, $c_y$, and $c_z$ |
| $F_{1x}$ | −9.215 | N | Measured at 10:22:08, for $c_x = -0.0350$, $c_y = -2.7425$, and $c_z = 2.5650$ |
| $F_{1y}$ | −32.729 | N | Measured at 10:22:08, for $c_x = -0.0350$, $c_y = -2.7425$, and $c_z = 2.5650$ |
| $F_{2x}$ | −43.051 | N | Measured at 9:51:01, for $c_x = -5.4000$, $c_y = -0.5925$, and $c_z = -1.1075$ |
| $F_{2y}$ | −1.298 | N | Measured at 9:51:01, for $c_x = -5.4000$, $c_y = -0.5925$, and $c_z = -1.1075$ |

**Table 7.** Values of inertial forces – extremes in x and y axes.

However, when hypothetic basal variants $v_1$ and $v_2$ are used, the situation becomes very different. The magnitude of the inertia forces is significantly greater on both axes, both in the case of highway and unpaved road (off-road).

When considering the greater of the affecting inertia forces, the required securing force of the strap is in the case of a highway 7.56× greater ($F_{1y}$) than in the case of an inertia force arising from normative-stipulated values of acceleration coefficients ($F_{ny}$). On an unpaved road (off-road), the situation is presumably even worse because an inertial force value of 27,410 N ($F_{2x}$) on the x-axis was calculated from the measured values, corresponding to nearly eight times the value of the inertial force calculated based on norm-stipulated values of acceleration coefficients ($F_{nx}$). In a simplified way, one might say that, using this extreme value, a cargo "behaves" as if it weighed 2741 kg instead of 500 kg.

Should the data from the moment of transportation (including sustaining the direction of impact) be used to construct the model, where the greatest acceleration coefficient value was measured (−2.7425 in the case of a highway and −5.4000 for off-road conditions, respectively), the situation would be as follows (see **Table 7**).

As apparent from **Table 7**, extreme inertial forces affect the cargo in isolated cases, fundamentally exceeding expected values. In the case of a value of −5.4000 for off-road conditions, the value of the respective inertial force affecting the cargo (securing strap) is −43.051 N. If we abstract it from its direction, it is 12.39× greater than the expected value corresponding to the acceleration coefficients from the EN 12195–1 norm. The cargo therefore "behaves" as if it weighed 4305 kg.

## 6. Conclusion

The importance of researching cargo securing in road transportation is apparent both from the study presented (chapter) and, in particular, from the estimated number of accidents caused by improperly or insufficiently secured cargo. The significance of cargo securing also rises in the context of multimodal transportation where the manipulation and transportation units must be prepared for the transportation effects in more than one form of transportation. With few exceptions, road transport is a necessary part of the door-to-door concept of multimodal transportation.

The initial requirement should be the collection of relevant data concerning accidents that are typically unavailable on national level. A specific overview regarding the number of accidents caused by improper or insufficient cargo securing would enable a strict focus on the specific causes of accidents and taking adequate measures. Such statistics would also verify, or disprove, the significance of impact (acceleration coefficients) on various types of surfaces, in different countries and for various types of vehicles and cargo.

However, the problem is not only in obtaining the data but also in their suitable statistical processing. Each isolated differentiation should not be considered in the case of a common cargo, but statistically significant divergences should be included in calculations. Further analysis including occasional extreme divergences is necessary in the case of sensitive cargo (dangerous, fragile, etc.) that may cause extensive damage to property and injuries to the driver or other road traffic participants.

A separate area for further study is also the services of the integrated emergency system, as well as the army, where the requirements are very specific. The outputs, particularly for unpaved roads (off-road conditions), would be particularly effective and useful for these two segments.

Another area of study will be the differentiation of approaches to cargo securing according to the expected transport route—road networks used. This is an analogy to the multimodal transportation where, at least implicitly, the “worst” form of transportation is considered. In this case, from the perspective of the basal variant, the form of transportation where the effect of inertial forces is expected to be greatest is considered “worst.” The resulting model would reflect magnitudes of acceleration coefficients for various road networks, for example, according to standard classification:

**a.** Highways, speed roads, and Class I roads

**b.** Class II and III roads (possibly including local roads)

**c.** Unpaved roads (off-road conditions)

The respective basal variant would be used for the category given, having been identified using sufficient scientific methods. Aside from standard statistics tools, there is also an option to use the method of spectral analysis or possibly Fourier transform.

The use of upgraded software supposes that it would serve as a welcome addition to existing software and could reflect the type of road, specifically the variants mentioned, and would be of indisputable advantage.

Software support should enable the verification of expected inertia forces, as well as dynamic simulation, for example, on the basis of the MSC ADAMS Multibody Dynamics (MBD) software that provides the opportunity to create mathematical models of transport vehicles and analyze cargo stress during vehicle movement.

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