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Risks of Goods Transport Focused on the Assessment of Semi-Trailer Dynamics on Highways for Cargo Securing

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Abstract: The issue of the transport of goods is well-known, yet, in practice, there are often cases of damaged shipments due to improper storage and inappropriately chosen transport technology. Many cases are due to ignorance of the basic characteristics of the cargo and, consequently, its transport characteristics. Vehicle dynamics is crucial to the design of proper cargo securing; therefore, this article provides the values of longitudinal and lateral acceleration of a 16.5 m semi-trailer vehicle combination for test routes of length of 10,827 km on highways and other roads in Slovakia, Austria, and Germany from the monitoring of goods. The horizontal acceleration of 0.2 g is considered as the minimum stability of the load unit that should withstand transport. A load unit with a stability from 0.2 g to 0.3 g could be considered as the weakest load unit. The test results show that even the weakest load units such as these can be damaged in transports, as semi-trailer vehicle combinations still reach longitudinal ax1000 and lateral ay1000 accelerations between 0.2 g and 0.3 g relatively frequently. Acceleration events higher than 0.3 g occur very rarely, at 1.4 event/1000 km for roads, but only 0.1 event/1000 km for highways from our test transports. We have demonstrated through our research that it is necessary for the load units to have a minimum stability of 0.2 g. We can conclude that load units with a stability of less than 0.2 g are completely unacceptable for transport without additional securing because we obtained 70.3 acceleration events per 1000 km in the interval from 0.1 g to 0.2 g on highways but 1148.1 events per 1000 km on other roads. There is a big difference between the number of acceleration events per 1000 km on roads and highways for all acceleration intervals, which means that there is a substantially lower probability of damaging the weak load units on highways than on other roads.

Keywords: cargo securing; accelerometer; acceleration; semi-trailer; monitoring of goods

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Citation: Jagelčák, J.; Kubáňová, J. Risks of Goods Transport Focused on the Assessment of Semi-Trailer Dynamics on Highways for Cargo Securing. *Appl. Sci.* **2024**, *14*, 3846. https://doi.org/10.3390/app14093846

Academic Editors: Vittorio Solina, Antonio Cimino, Eugénio Miguel Rocha and Radu Godina

Received: 6 March 2024
Revised: 23 April 2024
Accepted: 25 April 2024
Published: 30 April 2024

1. Introduction

The Slovak Republic is one of the countries with a well-developed transport infrastructure, which enables the transport of people, goods, and services. The share of the transport sector in the EU GDP is around 5%. The proportion of workers employed in this sector is more than 10 million, which implies its important position in terms of the economic and social importance to the state. Efficient transport systems are the basis for the ability of European companies to compete in the world economy. The quality of transport services has a major impact on people's quality of life. On average, 13.2% of each household's budget is spent on transporting goods and services.

According to EU statistics, the transport of goods has been on an upward trend since 2018. In Figure 1, we can see the main trends in road freight transport in the EU from 2018 to 2022. Domestic transport by type of goods and distance is analyzed, as well as goods transported on the national and international market [1].

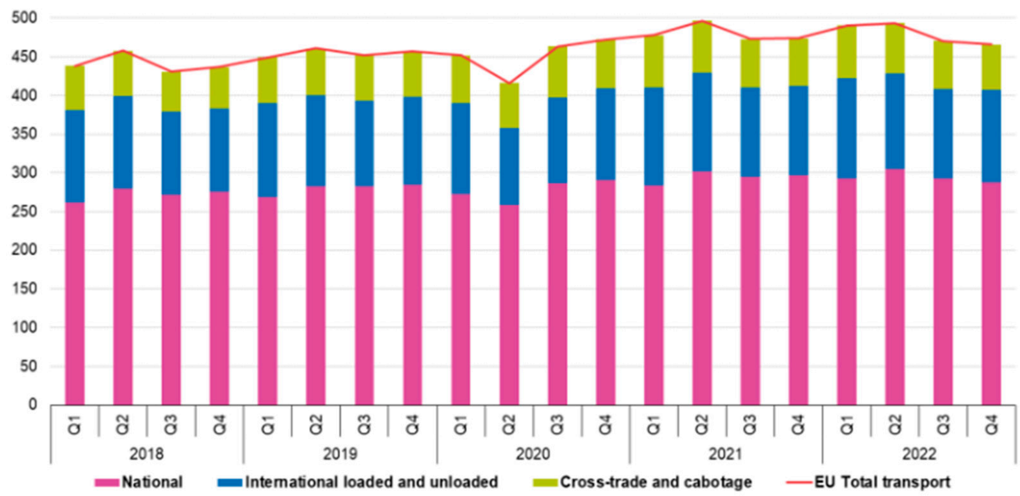

Figure 1. Quarterly road freight transport by type of operation, EU, 2018–2020, in billion tonne–kilometres. *Legend*: axle–x: year; axle-y: transport capacity in billion tonne–kilometres.

During transport, the material must be prevented from moving in any direction. The load must be placed on the vehicle in such a way that it cannot endanger persons or goods and cannot move or fall on the vehicle. However, accidents and crashes occur on the road every day as a result of the improper stowage and/or securing of cargo. Traffic accidents caused by lorries in Slovakia have remained at around 1000 in recent years. Last year, there were 1035, which was 34 fewer than the year before.

All parties involved in logistics, including packers, loaders, transport companies, operators, and drivers, are involved in ensuring that cargo is properly packed and loaded into the appropriate vehicle. It is very important to recognize that the responsibility for securing cargo is based on international conventions and regulations, national legislation, and/or contracts between the parties involved.

Although the IRU study showed that the truck load was the main cause of the accident in only 1.4% of cases (nine accidents) of all accidents in the database, in three of the nine crashes, the truck overturned. The study also showed, however, that cargo can contribute to the severity of the accident. Based on the 624 accidents in the database, fatigue was the main cause in only 6% of the accidents; 37% of these accidents were fatal. When fatigue played a role in the accident, 68% of these accidents involved a truck and another vehicle, and, in 29% of the cases, the accident was a single-truck accident. Regarding the time of the accident where fatigue was the main cause, two times during the day were identified as crucial. Most accidents happen between 02:00 and 02:59, probably the time when the driver's biorhythm is at a low point, and from 15:00 to 15:59, when it is nearly the end of the working day. Regarding the place of accidents where fatigue is the main cause, nearly 90% happen on highways or on inter-urban roads. Fatigue as an accident cause plays only a minor role in cities [2–4].

Acceleration is an important quantity in dynamics and allows us to describe how forces affect the motion of objects. If an object is acted upon by forces that are in equilibrium, its velocity need not change, and the acceleration will be zero. On the other hand, if the force is unbalanced, the acceleration will be non-zero and the object will move faster or slower. It can be recorded by an accelerometer, which records the reaction that occurs during acceleration. MEMS sensors have the power to transform industries by measuring physical quantities; MEMS sensors are miniature devices used to measure physical quantities such as pressure, temperature, acceleration, and magnetic fields. MEMS are very small systems, or systems made of very small components (micro—dimensional factor, electro—electronic element, and mechanics—mechanical element), and include electronic and non-electronic elements, process signals, control, and a display. MEMS are remarkable in that they can not only monitor parameters but also activate various mechanical processes. In addition to being able to work individually, they are also capable of co-operating with each other at the macro level—performing simpler tasks independently and handling complex functions in co-operation. They monitor, and then gather information by measuring, for example, mechanical, thermal, chemical, biological, magnetic, or optical events. The use of MEMS sensors is an effective method for measuring the dynamic parameters of a semi-trailer vehicle combination in transport. Our paper provides insights and recommendations for transportation professionals that can be useful for further research and applications in this field.

The paper focuses on the acceleration events during the transport of goods by a standard semi-trailer vehicle combination on highways, where the monitoring of a semi-trailer carrying cargo in both directions for one consignor and one consignee was used, which allows us to complete multiple transports along the same route. The transports were carried out from Slovakia to Germany from Monday to Friday. The transports in the opposite direction were carried out from Tuesday to Saturday. The transports from Slovakia to Germany were carried out from 19:00 to 07:00 next day, which means during the night, and from 15:00 to 02:00 next day in the opposite direction.

2. Literature Review

Road freight transport is the main mode of transport of goods in the European Union. Given this fact, pressure is being put on carriers to ensure that any transport of goods is fast, safe, inexpensive, and efficient. On the basis of these requirements, truck drivers are often forced to violate the conditions governing the work of drivers in the European Union and the rules of the road in force at the same time. As a result, the dangers on the roads are increasing and other road users are increasingly endangered. The European Union is striving to reduce the number of road accidents, particularly in terms of road deaths and their socio-economic costs. For these reasons, a number of commitments have been made by the European Union for the future to improve the education and training of road users, to improve the safety of road infrastructure, to promote the use of modern technologies, to improve emergency services, and, above all, to protect vulnerable road users. The main objective of European road safety policy is also highlighted in the White Paper in the Roadmap to a Single European Transport Area.

Road safety in the Slovak Republic is related not only to national road safety, but also to safe transport on European roads, in the context of the Slovak Republic's participation in the EU and the European area. The direction of the process of improving road safety in the Slovak Republic is based on the direction of the Government of the Slovak Republic and the European Transport Policy. Significant attention is paid to road safety issues in the White Paper 2050: Roadmap to a Single European Transport Area—Creating a competitive and resource-efficient transport system. Its list of initiatives includes tasks stemming, in particular, from Objective 1.4., high on the agenda for transport safety—Measures in the field of transport safety: saving thousands of lives. It is not only about harmonizing and developing new intelligent technologies and transport systems, but also about developing comprehensive strategic measures on road accidents, emergency services, definitions of injury, and fatality classifications in preparation for the adoption of the objective of reducing the number of accidents, focusing on user training and education, promoting the use of safety equipment and paying particular attention to the most vulnerable user groups such as pedestrians, cyclists, and motorcyclists, including by means of a safer infrastructure, vehicle technologies, and improved legislation [5].

The priority in the European area for 2011–2020 was to reduce the number of people killed in road accidents by 50% compared to 2010. By setting a new quantitative target and benchmark, the first three years of the decade saw a real reduction in the number of deaths in line with the planned trend, but, since 2013, there has been a significant stagnation at the European level. The expansion of the COVID-19 programme and the associated reduction in mobility due to national measures aimed at partially restricting the free movement of the population to prevent the spread of the disease have also had some impact on this phenomenon. The development of the number of road facilities in EU countries can be sees in Figure 2.

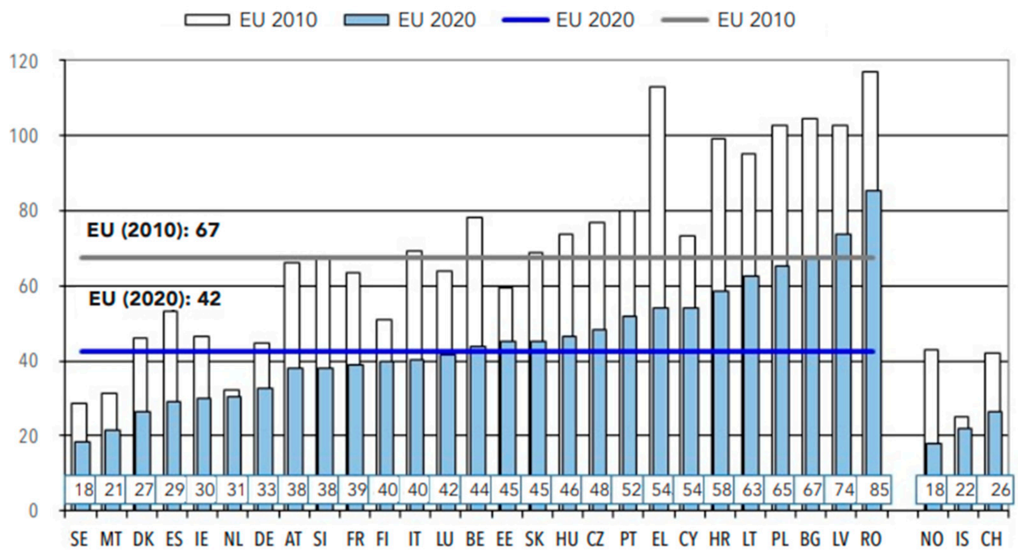

Figure 2. Development of the number of road fatalities per 1 million inhabitants in EU countries, comparing between 2010 and 2020 [5]. *Legend*: axle–x: EU countries; axle-y: number of deaths per 1 million inhabitants.

One of the basic principles of the current strategy to improve safety at the EU level is to strive for higher safety standards in the transport system—creating a safe transport area, but, at the same time, placing the main responsibility for their own safety and the safety of others on the road users themselves, who are at the center of the system. An integrated approach will be used to create a safe transport area in order to integrate the safety element into the other EU elements of economic and social policy [6].

According to the author [7], it is important to examine all types of road infrastructure in traffic accidents. His study concluded that the use of goods vehicles is shown not to be unduly hazardous compared with the use of other motor vehicles in terms of aggregate risk, but, in accidents involving goods vehicles, the numbers of casualties to other kinds of road users are substantially greater than those to the goods vehicle users themselves.

Current developments in the geopolitical situation also have a significant impact on international transport and important transport links; therefore, the diversification of these threats is a logical factor to ensure the efficient supply of goods and, thus, the development of international trade [8]. The role of the transport sector is to meet the demands of the market in terms of the quality, flexibility, speed, and safety of transport of people and goods [9]. To ensure the safety of transport systems, the diagnostics of these systems and equipment is important. Many indicators are used to compare the level of road safety in many countries, including the most popular demographic indicators. Road safety management systems are more complex solutions.

Most studies focusing on road freight transport safety point to accidents in the urban infrastructure. This is mainly because, in urban logistics, VRUs (vulnerable road users) are particularly at risk in a truck accident. Yet, when driving on motorways, collision with VRUs is at a minimum level. Moreover, in this study [10], the authors investigate the impact of urban freight on VRU safety during the rapidly growing era of urban freight transport by examining the incidence of freight and VRU crashes. They continue to understand when, how, where, and under what circumstances truck and VRU crashes occur.

Reducing the frequency and severity of road crashes continues to be a priority for traffic and transportation engineers. The UN Decade of Action for Road Safety (2010–2030) has highlighted the need for road designers and authorities to better understand the complexity of the causes of road crashes and the severity of injuries, and to work more proactively to reduce the potential for high-severity crashes. The UN has defined a series of road safety targets that countries around the world have committed to achieving. These include better road traffic management strategies, which, in turn include better systems for understanding the causes of road crashes.

Road safety analyses can be useful in identifying stretches of national roads that are prone to a high crash incidence and high injury severity, as well as identifying factors that contribute significantly to a high crash incidence [11]. Estimating the factors influencing crashes on a given rural state road is important for evaluating various covariates and alternative road design variables [12,13], as well as for understanding which factors may be more challenging for drivers than commonly assumed. A variety of methods are used to conduct the road safety analysis, with several statistical methods commonly used by road engineers [14–16].

Vehicle movement monitoring is commonplace in today's intelligent age, whether for safety or competitiveness. A number of sensors are used for monitoring, each with its own significance. The authors in [17] focus on the growing part of electronics in automobiles and present automotive applications of MEMS. Currently, a car contains about 50 sensors not only for engine control but also for safety and passenger comfort. Nowadays, automotive MEMS applications are a major trend to improve safety and comfort in the vehicle. In recent years, the development of advanced driver assistance systems (ADASs) to fully automated vehicles (AVs) have focused on innovations in transportation, real-time infrastructure-to-vehicle and vehicle-to-vehicle connectivity, automation in transportation systems for people and goods, and smart agriculture, including safety driving, navigation and positioning systems, traffic flow management, and pollution control. One of the key points of safe development is related to the accuracy and reliability of sensors used in multi-sensor networks, and, hence, to traceable metrological characteristics based on standard procedures and/or experimental methods that are generally agreed upon [18].

As is well-known, gyroscopes in combination with accelerometers are essential components of inertial measurement units (IMUs) integrated into vehicles to detect the amplitude and direction of applied forces, angular velocity, and orientation. Recently, based on suitable calibration procedures that are currently available, it is possible to ensure the metrological traceability of digital 3-axis MEMS accelerometers for both inertial and dynamic conditions with proper accuracy and precision from traceability budgets and detailed uncertainties [19,20].

It has already been mentioned several times that the safety of transporting goods is an important factor. This security is the responsibility of the parties involved in the transport in question. The consignor is liable for the correct marking and packaging of the goods. The loading organization is liable for loading the goods, the driver for the correct stowage and securing of the cargo on the vehicle, and the carrier for the selection of a safe route and the transport itself.

According to the convention on the contract for the international carriage of goods by road (CMR), the carrier is liable for the total or partial loss of the consignment or for damage to the consignment arising from the time of acceptance of the consignment for carriage until the time of its delivery, as well as for any overrun of the delivery period [CMR]. The liability of the carrier is thus presumed. The carrier may be exonerated from liability if he proves that the loss of the consignment, its damage, or the exceeding of the delivery period was due to fault of the following:

- the beneficiary;
- an order of the authorized person which was not due to the negligence of the carrier;
- the shipment itself;
- circumstances beyond the carrier's control and the consequences of which are beyond the carrier's power to remedy.

The burden of proving these facts is on the carrier.

The carrier shall likewise be exempt from liability if the loss or damage arises from a special danger connected with at least one of these facts:

- the use of open vehicles without tarpaulins (if such use of vehicles has been expressly agreed upon and noted in the consignment note);
- the missing or defective packaging of the consignment (which, by its nature, if not properly packed or not packed at all, is liable to loss or damage);
- the handling, loading, stowage, or unloading of the consignment by the consignor, consignee, or persons acting for the consignor or consignee;
- the inherent nature of certain goods (for which they are subject to total or partial loss or damage, in particular, by breakage, rust, internal deterioration, desiccation, leakage, normal decay, or exposure to insects or rodents);
- insufficient or defective markings or numbers of individual items of the consignment;
- the carriage of live animals.

If the carrier certifies that the damage may have arisen from any of these hazards, the burden of proof shall pass to the customer. The customer must prove that the damage was caused partly or wholly by another cause [21].

The carrier is obliged to take out insurance against liability for damage caused by the operation of the vehicles and the activities of the vehicle crews to consignors, consignees, and, where applicable, third parties. The insurance cover of the road carrier's liability insurance should correspond to the amount of the carrier's liability, which is different in national and international road transport. The liability of the carrier in road haulage is limited according to the legislation under which the contract of carriage is concluded. In the case of national road haulage, the contract of carriage is governed by the Commercial Code and the Civil Code, while the conclusion of the contract of carriage in international road haulage is governed by the CMR Convention.

As mentioned above, safety is one of the key aspects of successful cargo transportation. In the case of road transport, vehicle dynamics during routine events such as braking, steering, and evasive maneuvers are variable at different points on the vehicle. Several manufacturers supply different dataloggers with acceleration sensors, but the results are not comparable due to the different sensor parameters, measurement ranges, sampling frequency, data filtering, and evaluation of different acceleration periods. The position of the sensor in the load area is also important. Accelerations are not the same at all points on the vehicle. This paper deals with the measurement of these dynamic events using MEMS sensors at a selected location on a vehicle loaded with cargo and the changes in dynamics after certain events that might occur during the normal road transport of cargo, in order to analyze the possibilities of monitoring accelerations and associated forces acting on the cargo during transport [22–24].

The research is new in terms of identifying the intensity of acceleration events in the longitudinal and lateral direction for the cargo securing of semi-trailer vehicle combinations and transport stability of load units when driving on highways.

3. Materials and Methods

3.1. Sensors

MEMS are low-cost and high-precision inertial sensors that are used in a wide range of industrial applications. These sensors use chip-based technology, specifically a micro-electromechanical system. These sensors are used to detect and measure external stimuli. Whenever an MEMS sensor applies a tilt, the balanced mass causes a difference in electrical potential. This can be measured as a change in capacitance. Then, this signal can be changed to produce a stable output signal in digital form, 4–20 mA or VDC [25,26]. The parameters of the sensor used by us are given in Table 1. MEMS sensors are used in a variety of fields which include automotive, consumer, industrial, military and biotechnology, space research, and commercial applications which include inkjet printers, accelerometers in modern automobiles, consumer electronics, personal computers, etc. MEMS sensors are also used in the automotive industry to measure acceleration, tilt, vibration, and motion to provide motion detection and stability control capabilities. It enabled us to measure the necessary accelerations in our research.

Table 1. Sensor parameters.

Sensor	3—Axis Accelerometer and Gyroscope IMU	GNSS Dual-Band Sensor
Sensor description	STM LSM6DSO (STMicroelectronics: Geneva, Switzerland) MEMS accelerometer +/− 8 g MEMS gyroscope +/− 500 dps [X]	GPS: L1 + L5 Galileo: E1 + E5a GLONASS: G1 Beidou: B1I + B2a Navic
Sampling frequency	200 Hz	1 Hz

Advantages of using MEMS sensors include, for example, low power consumption, low-cost manufacturing, and resistance to shock, radiation, and vibration. We see the investment involved in development as a disadvantage.

Three-axis accelerometers supplied for the consumer market are typically calibrated by the sensor manufacturer using a six-element linear model comprising a gain and offset in each of the three axes. This factory calibration will change slightly as a result of the thermal stresses during soldering of the accelerometer to the circuit board [25]. An accelerometer is an electromechanical device that measures acceleration forces. These forces may be static, like gravity, or they could be dynamic—caused by moving or vibrating. There are many types of accelerometers and there are many different ways to make an accelerometer. Some accelerometers contain microscopic crystal structures that get stressed by accelerative forces using the piezoelectric effect. Another sensing change is in capacitance. Capacitive sensing has excellent sensitivity [26]. An accelerometer is the primary sensor responsible for measuring inertial acceleration or change in velocity over time and can be found in various types including mechanical accelerometers, quartz accelerometers, and MEMS accelerometers.

3.2. Test Vehicles

Two typical 16.5 m-long semi-trailer vehicle combinations for transporting packaged goods, consisting of a two-axle tractor and a three-axle semi-trailer with a three-sided folding tarpaulin with EN12642 Code XL certificate, were used for transport monitoring: The first set with an Iveco S WAY AS440ST/FP LT BA3C tractor unit (manufactured in 2022) and a Schwarzmüller—J—Serie S1 semi-trailer (manufactured 2019), and the second set with a Mercedes-Benz Actros 963-4-A tractor unit (manufactured in 2022) and a Schmitz Cargobull—SCB*S3T semi-trailer (manufactured in 2022).

Two drivers were deployed for both vehicle combinations. The transports, therefore, involve a two-way loaded vehicle between Slovakia and Germany and back with two vehicle combinations and four drivers. The total weight of the load is from 4 to 13 tonnes in the semi-trailer.

The sensor was placed under the loading area in the middle of the loading area of the semi-trailer (see Figure 3).

Figure 3. Sensor positioning on the 16.5 m semi-trailer vehicle combination.

3.3. Test Routes

The measurements were carried out on two different semi-trailer vehicle combinations and on 15 routes. The routes can be divided into:

- Routes from Žilina/Martin (Slovakia) towards Munich (Germany);
- Routes from Munich (Germany) towards Žilina/Martin (Slovakia).

Table 2 shows the total distance travelled through the individual countries. From this, we have identified the total distance for highways and other roads. Highway feeder roads were considered as part of the highway, as well as entrances and exits from highway parking.

Table 2. Total distance in kilometers travelled on highways and other roads per country.

	Slovakia (SK)	Austria (AT)	Germany (DE)	Total
Highway	2878	4929	2302	10,109
Road	284	27	406	718
Total	3163	4956	2708	10,827

Source: authors.

Testing routes travelled with the indication of highways and other roads are in Figure 4.

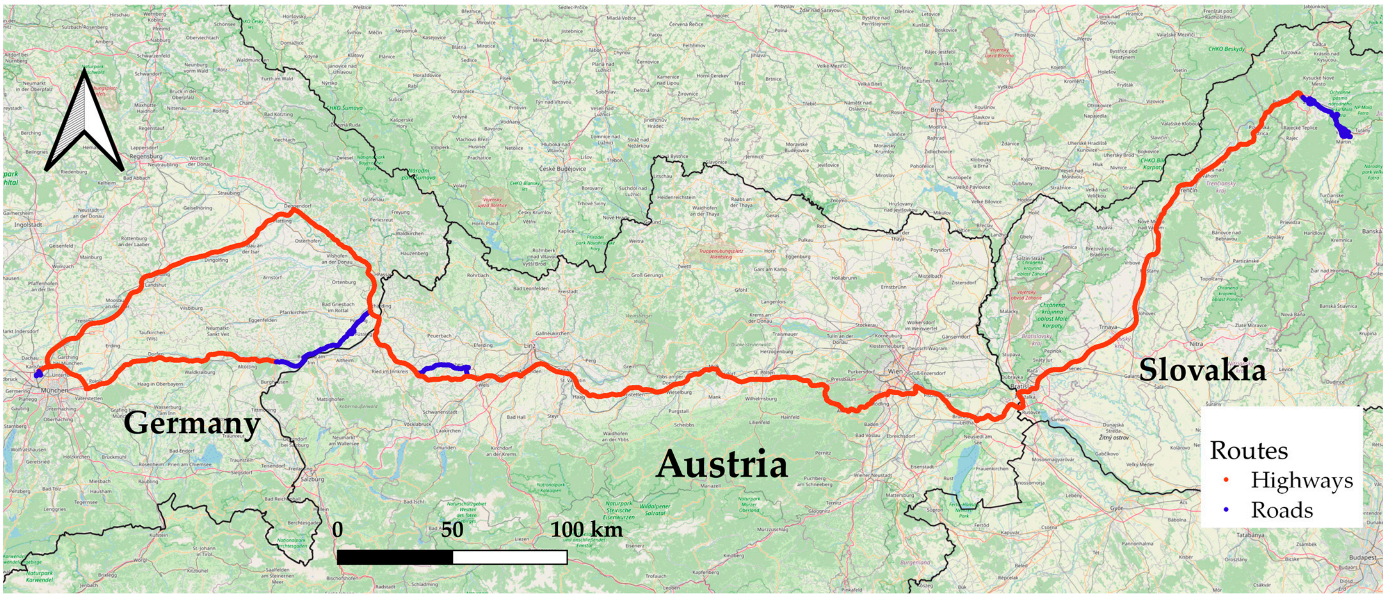

Figure 4. Testing routes with indication of highways (red) and other roads (blue) on OpenStreetMap (OSM) map layer [authors].

Highways and other roads account for 93.4% and 6.6% of the routes tested, respectively. The testing focused on the accelerations achieved by the semi-trailer combinations when driving on highways. Slovakia accounts for 29.2%, Austria 45.8%, and Germany 25.0% of the total distance travelled.

3.4. Evaluation of Data

Accelerations and speeds on the given routes were monitored in two axes, in the longitudinal direction on the x-axis with the deceleration and acceleration values and in the lateral direction on the y-axis for right-turn and left-turn events. Accelerations were evaluated as maximum average value in time interval of 80 ms, 300 ms, and 1000 ms. The method for determining the evaluation times is described in [22].

On the x-axis in the longitudinal direction, accelerations were measured during vehicle braking and acceleration. There are negative values on the x-axis when the vehicle combination is braking and positive values when it accelerates. In the lateral direction on the y-axis, lateral accelerations were measured during cornering. They took positive values in the case of right-turn events and negative values in the case of left-turn events.

Acceleration event is considered the event where acceleration ax300, ay300, or az300 in 300 ms exceeds 0.1 g for a period of at least 1 s. Evaluation time of 300 ms to select acceleration events higher than 0.1 g was used due to standard EUMOS 40509 [27] that describes that the testing platform decelerates for 300 ms until the platform is stopped. We can consider acceleration event according to this standard that lasts at least 400 ms [28]. But the standards EN 12642:2016, prEN17321:2021, DIN 55415:2022, and SS 17321:2022 [29–32] requires us to obtain maximum average acceleration in 1000 ms for testing of vehicle bodies, cargo securing, and stability of load units by driving tests. Therefore, we have used 300 ms acceleration profile to select acceleration event but maximum value of the event is evaluated in 1000 ms. Further, only acceleration events that last at least one second above 0.1 g are analyzed because the cargo securing is focused on long-duration acceleration events. We have decided to select the filter level of acceleration events of 0.1 g because of road/vehicle inclination which influences the values below 0.1 g. This filter level is also used by Ge et al. [33] but their research is more focused on comparison of rise time of acceleration event (jerks) with the standard EUMOS 40509 and the methodology is based on the theory of evaluation of shocks. Our method is not suitable for analyzing rise times (jerks) but is suitable for evaluating acceleration events of ax1000 and ay1000 for cargo securing. Other researchers focused on military vehicles but they are not using evaluation times for evaluation of acceleration coefficients [34–37]. Our previous research of driving tests for delivery van dynamics [38,39] were focused on calculation of curve radii and influence of sensor position for delivery van. Authors of [28] were focused on unit load packaging using acceleration test according EUMOS 40509 but they have not evaluated accelerations from these tests.

We have also monitored accelerations in vertical axis but there were no acceleration events in z-axis fulfilling these evaluating conditions which means that acceleration events in z-axis are rather short in duration. Acceleration events were evaluated in MATLAB® R2023a.

4. Results

4.1. Longitudinal Accelerations

If we examine longitudinal accelerations, which are important from the point of view of load securing in the forward and rearward directions, we have to distinguish between the different directions, as the vehicles do not behave the same in both directions. In the forward direction, the deceleration values are more intense than when the vehicle is starting up, and, therefore, the vehicle has higher negative acceleration values here. The forward direction is considered the most critical direction for load securing and transport stability of load units, because, for vehicles with a gross vehicle mass (GVM) above 3.5 t, the designed acceleration for load securing and transport stability of load units in road transport according to EN 12195-1:2010 [40] in the forward direction is 0.8 g and, in the rearward direction, 0.5 g, with an evaluation time of 1000 ms, according to EN 12642:2016, being essential.

In Table 3, we can see the maximum and minimum values of the accelerations on the x-axis at the times of 80 ms, 300 ms, and 1000 ms from all testing routes. The minimum acceleration values were measured on the motorway in Austria (see Figure 5) at all three evaluation times (the same acceleration event). This occurred during a braking of a duration of 1.2 s from 80 km/h to 70 km/h; i.e., it was not a sudden hard braking to a stop as performed in the braking tests.

The maximum acceleration values of the semi-trailer combination were measured on the road in Slovakia at all three evaluation times (the same acceleration event) during the acceleration from 0 to 22 km/h. A similar maximum acceleration $ax1000 = 0.22$ g was also achieved on the highway in Austria and Germany. The designed rearward acceleration of 0.5 g is normally achieved by braking the semi-trailer in the rearward direction, which itself was not used even once during the test runs. This shows that the semi-trailer combination does not accelerate by more than half of the designed rearward acceleration. Higher accelerations rearwards can occur during hard braking rearwards which is generally not used during regular transports but is used during braking tests as per EN12642:2016.

Table 3. Maximum measured deceleration (negative values) and acceleration (positive values) of semi-trailer vehicle combination in longitudinal axis in 80, 300, and 1000 ms evaluation times.

		MIN ax80	MAX ax80	MIN ax300	MAX ax300	MIN ax1000	MAX ax1000
Slovakia	Highway	−0.235	0.183	−0.204	0.172	−0.187	0.146
	Road	−0.505	0.276	−0.463	0.261	−0.395	0.222
Austria	Highway	−0.660	0.248	−0.623	0.245	−0.492	0.221
	Road	−0.325	0.180	−0.311	0.174	−0.259	0.165
Germany	Highway	−0.213	0.242	−0.202	0.238	−0.193	0.217
	Road	−0.330	0.210	−0.324	0.201	−0.295	0.188
	Total	−0.660	0.276	−0.623	0.261	−0.492	0.222

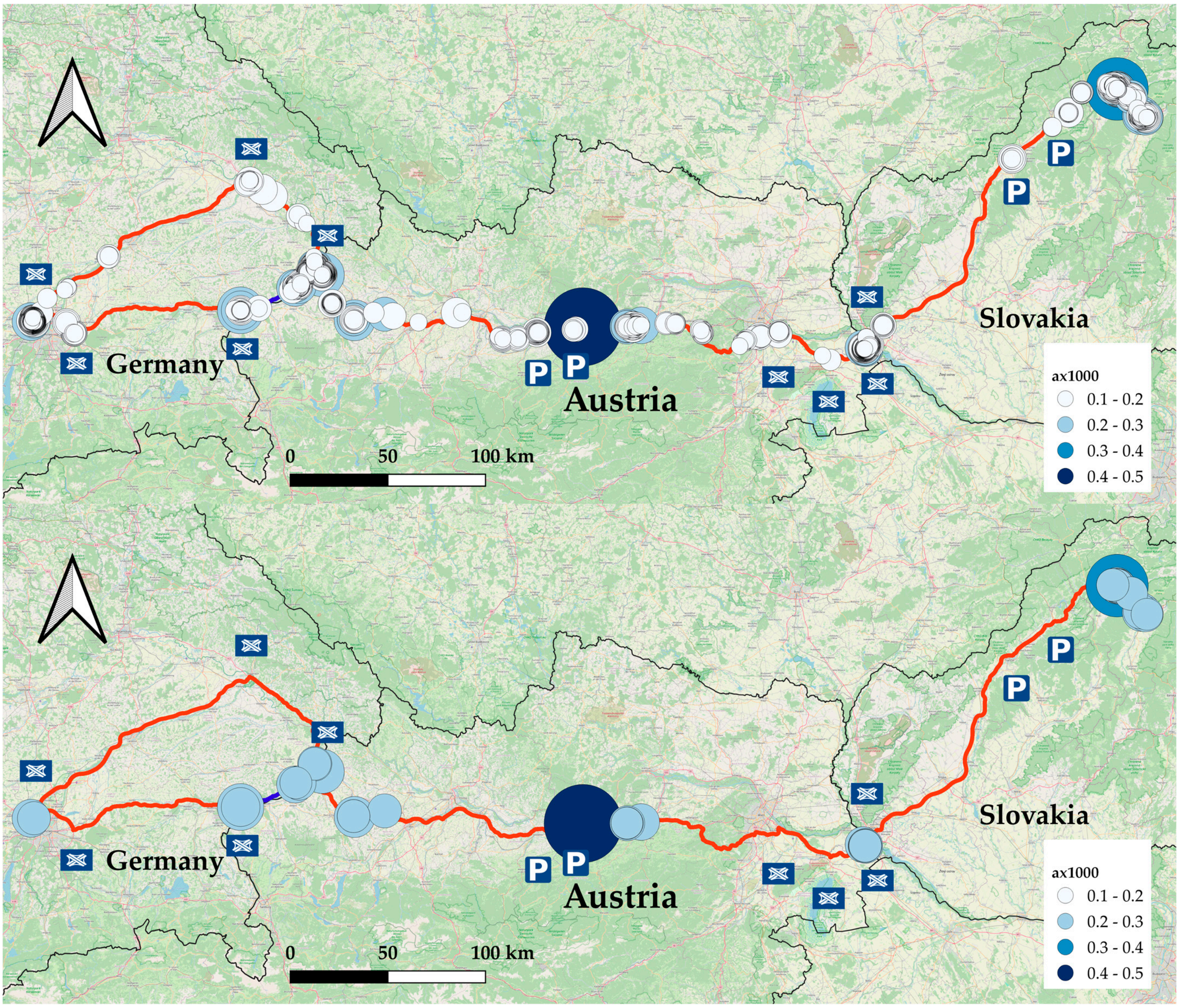

Figure 5. Acceleration events in the ax1000 (absolute values) from 0.1 g to 0.5 g (**top**) and from 0.2 g to 0.5 g (**bottom**) with the indication of selected parking and highway intersections on OSM map layer.

It can be seen from the above values that the semi-trailer combination did not achieve the design accelerations for securing the load in the forward or rearward direction in either case, even for the shortest evaluation time of 80 ms. It can also be seen that a higher negative acceleration is achieved during braking than the positive acceleration when the vehicle is accelerated.

Table 4 shows the total number of x-axis acceleration events longer than 1 s from all testing routes. There are 57.7% deceleration events and 42.3% acceleration events; 53.9% of the deceleration events are in the interval from –0.2 g to –0.1 g and 41.6% acceleration events are in interval from 0.1 g to 0.2 g. There are only 3.8% of the deceleration events and 0.76% of the acceleration events higher than 0.2 g which is the minimum stability of the load unit that should withstand transport.

Table 4. Number of x-axis acceleration events per country on highways and roads for ax1000 ranging from –0.5 to –0.1 g and from 0.1 to 0.3 g.

Acceleration Events [g]		**Slovakia**			**Austria**			**Germany**		**Total**
ax1000	**Highway**	**Roads**	**Total**	**Highway**	**Roads**	**Total**	**Highway**	**Roads**	**Total**	
[–0.5; –0.4)				1		1				1
[–0.4; –0.3)		1	1							1
[–0.3; –0.2)		10	10	9	2	11		7	7	28
[–0.2; –0.1)	42	85	127	126	2	128	56	114	170	425
[0.1; 0.2)	12	65	77	106	1	107	53	91	144	328
[0.2; 0.3)		2	2	2		2	2		2	6
Total	54	163	217	244	5	249	111	212	323	789

For better clarity, the individual accelerations at 1000 ms are displayed in Figure 5 in absolute values (acceleration and deceleration together). The color and size of the points indicate the intensity of the x-axis acceleration event.

There are 36 longitudinal acceleration events above 0.2 g, of which 22 happened on roads and 14 on highways.

4.2. Lateral Accelerations

If we examine the lateral accelerations, which are important from the point of view of load securing in the lateral direction, we can distinguish between the different directions, but, in the long run, the number of left-turn and right-turn events are about the same. For vehicles with GVM above 3.5 t, the designed acceleration for the load securing and transport stability of load units in road transport in the lateral direction is 0.5 g and 0.6 g in the case of unstable loads, whereby an evaluation time of 1000 ms, according to EN12642:2016, is essential.

In Table 5, we can see the maximum and minimum values of the y-axis accelerations at evaluation times of 80 ms, 300 ms, and 1000 ms from all testing routes. The largest measured values of the right-turn event were measured in Slovakia in the city of Zilina (see Figures 5 and 6) at all three times (the same acceleration event) during the drive through the right-turn flyover intersection with a speed between 29 and 51 km/h.

On the other hand, the largest measured values of right-turn events were measured on a city curve in Slovakia in the city of Žilina (see Figure 6 and Figure 8), also at all three evaluation times (the same acceleration event) during the drive through the left-turn curve with a speed between 71 and 83 km/h.

Table 6 shows the total number of the y-axis acceleration events from all testing routes. There are 38.2% left-turn events and 61.8% right-turn events; 35.6% of left-turn events are in the interval of –0.2 g to –0.1 g and 54.9% of right-turn events are in the interval of 0.1 g to 0.2 g. There are only 2.7% of left-turn events and 6.8% of right-turn events higher than 0.2 g, which is the minimum stability of the load unit that should withstand transport.

Table 5. Maximum measured acceleration of left-turn event (negative values) and right-turn event (positive values) of semi-trailer vehicle combination in lateral axis in 80, 300, and 1000 ms evaluation times.

		MIN ay80	MAX ay80	MIN ay300	MAX ay300	MIN ay1000	MAX ay1000
Slovakia	Highway	−0.265	0.334	−0.234	0.299	−0.219	0.274
	Road	−0.311	0.347	−0.297	0.338	−0.285	0.330
Austria	Highway	−0.293	0.370	−0.280	0.337	−0.274	0.323
	Road	−0.234	0.261	−0.229	0.253	−0.224	0.245
Germany	Highway	−0.245	0.323	−0.209	0.305	−0.190	0.299
	Road	−0.282	0.309	−0.261	0.297	−0.240	0.266
	Total	−0.311	0.370	−0.297	0.338	−0.285	0.330

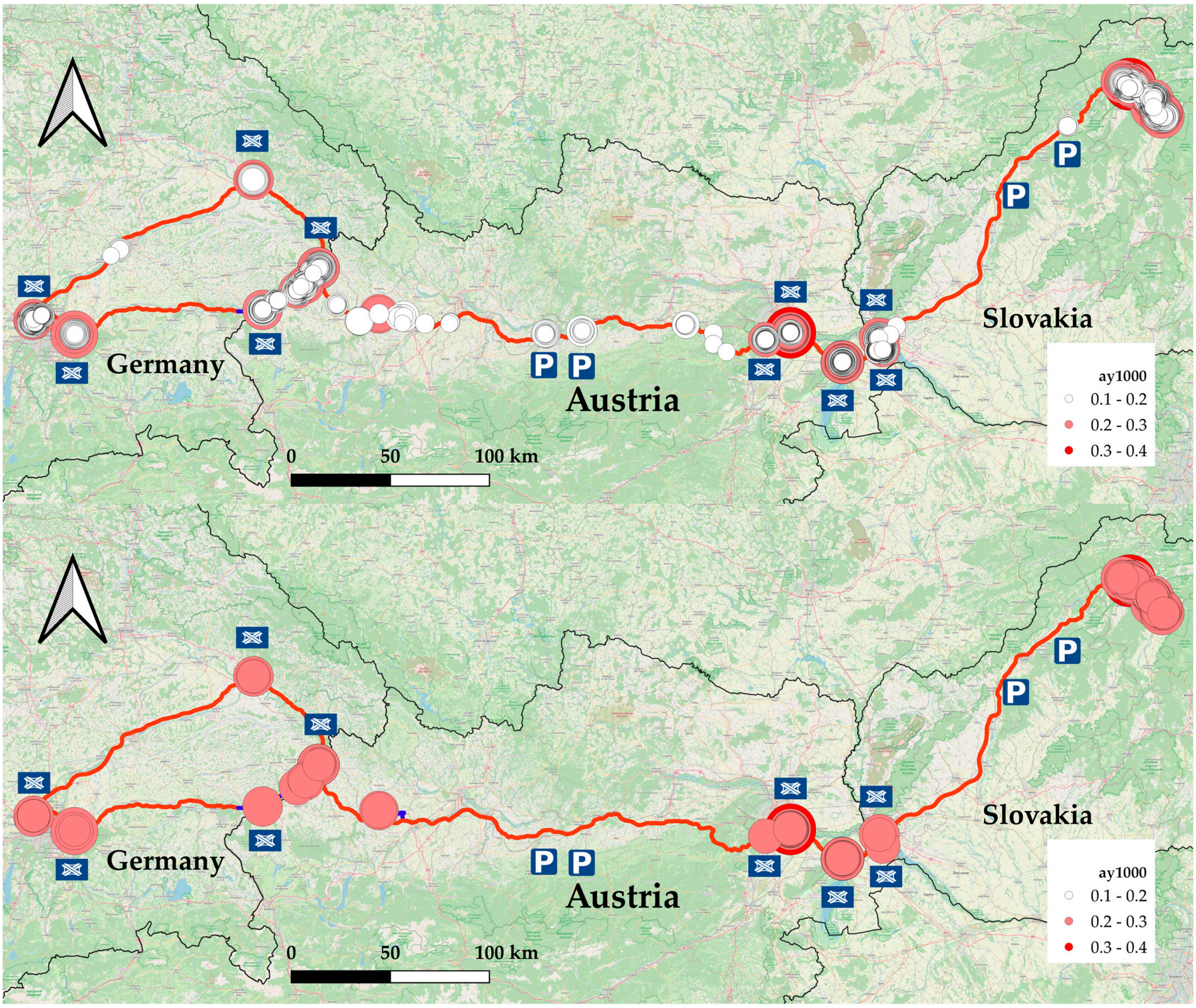

Figure 6. Acceleration events in the ay1000 (absolute values) from 0.1 g to 0.4 g (**top**) and from 0.2 g to 0.4 g (**bottom**) with indication of selected parking and highway intersections on OSM map layer.

Table 6. Number of y-axis acceleration events per country on highways and roads for ay1000 ranging from –0.4 to –0.1 g (left-turn events) and from 0.1 to 0.4 g (right-turn events).

Acceleration Events	Slovakia			Austria			Germany			Total
ay1000	**Highway**	**Road**	**Total**	**Highway**	**Road**	**Total**	**Highway**	**Road**	**Total**	
[–0.3; –0.2)	1	7	8	6	1	7		4	4	19
[–0.2; –0.1)	43	120	163	43	2	45	28	58	86	294
[0.1; 0.2)	66	172	238	81	5	86	54	109	163	487
[0.2; 0.3)	6	30	36	8	1	9	10	6	16	61
[0.3; 0.4)		1	1	1		1				2
Total	116	330	446	139	9	148	92	177	269	863

From the above values, it can be seen that the semi-trailer combinations did not reach the design accelerations for sideways load securing in either case, even for the shortest evaluation time of 80 ms, and it can be seen that the highest measured values for right-turn and left-turn events are approximately the same.

For better clarity, the individual accelerations at 1000 ms are displayed in Figure 6 in absolute values (left-turn and right-turn events together). The color and size of the points indicate the intensity of the y-axis acceleration event.

Most of the lateral acceleration events above 0.2 g happened on roads and highway intersections. There are 82 lateral acceleration events above 0.2 g, of which 50 happened on roads and 32 on highways.

5. Discussion

Sliding, tipping, rolling, wandering of all items of load, or serious deformation and rotation in any direction shall be prevented during transport by blocking, locking, lashing, or a combination of these methods. The reason for this is to protect persons during loading, unloading, and driving, as well as other traffic users, the cargo, and the vehicle. The load shall be stowed on the vehicle not endangering persons or other load units. The load shall not move on or fall from the vehicle platform.

However, accidents occur every day as a result of the improper stowage and/or securing of cargo. Therefore, packers, loaders, and haulers shall ensure that the cargo is packed properly and stowed in the appropriate vehicle. The responsibility for securing cargo is based on international and national conventions and regulations and/or contracts between the parties involved. The design of cargo-securing measures shall be based on acceleration values, safety factors, friction coefficients, and test methods, e.g., described in EN 12195-1:2010.

The general principle of load securing is to prevent movements of the load against the load platform in the longitudinal and transverse direction due to vehicle acceleration.

Examples of inadequate load securing are cargo transported on unsuitable vehicles, vehicle bodywork in poor condition, a situation where the vehicle does not have anchoring points for the load, the load being completely unsecured on vehicles, packages that are unsuitable for transport due to their low degree of stability, an improper method of loading, e.g., with gaps between load units or between load units and vehicle walls, the driver knowingly or unknowingly neglecting to secure the load, inadequate cargo-securing instructions from the shipper/loading organization to the carrier, top-over lashing as the most commonly used lashing method (not generally suitable for securing of heavy loads forwards), overloaded vehicles with improperly secured loads, and securing devices in poor condition. These deficiencies can cause damage to cargo and vehicles, as well as serious accidents.

We decided to focus on finding the accelerations of semi-trailer vehicle combinations when transporting cargo mainly on highways because of missing acceleration values for the load securing and transport stability of load units from real transports. We used two semi-trailer vehicle combinations with four drivers with a total distance traveled of 10,827 km. Most of the research is devoted to the study of passenger vehicle dynamics; therefore, data from actual transports for heavy goods vehicles are missing and, especially, for the purposes of the load securing and transport stability of load units.

It is necessary to verify the significant statistical differences between the directions, and countries, as well as vehicle combinations. If there is not a significant statistical difference, we can use all acceleration events for further analysis because there are no biases in data. The Kolmogorov–Smirnov test was used in Matlab (kstest) for the ax1000 and ay1000 maximum values of acceleration events. We can reject the null hypothesis for the normal distribution at the 5% significance level. Because of that, we used non-parametric Kruskal–Wallis tests in Matlab for different testing scenarios because they are statistically independent. The results for p-value are given in Table 7.

Table 7. Kruskal–Wallis test results for maximum ax1000 and ay1000 values of acceleration events and different testing scenarios.

Testing Scenario	*p*-Value	
	ax1000	**ay1000**
2 directions (SK-DE and back)	0.1400	0.1057
2 vehicle combinations	0.9021	0.1951
3 countries (SK, AT, DE)	0.0634	0.9713

We can state that the testing scenario has no statistically significant impact on the gathered data because all *p*-values are higher than 0.05.

Therefore, we can say that the route direction does not influence the gathered data as well as vehicle combinations and countries. Because the ax1000 *p*-value of 0.0634 is close to the decision limit, we provide the boxplots of the maximal values of the ay1000 of acceleration events for individual countries in Figure 7, where we can see very similar results between countries.

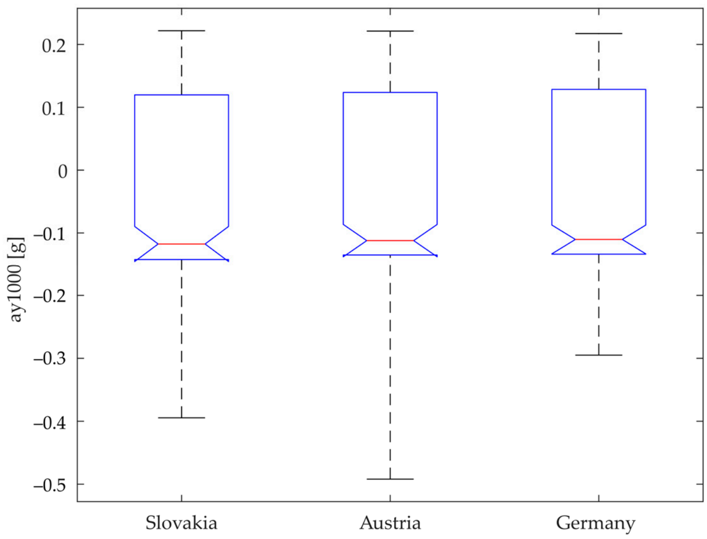

Figure 7. Box-plots of maximum values of acceleration events of ay1000 for individual countries from Kruskal–Wallis test from Matlab.

Highways and other roads account for 93.4% and 6.6% of the routes tested, respectively. Given that there is not an even representation of highways and roads, we chose to compare acceleration events relative to distance travelled. Here, we have chosen the calculation of the number of acceleration events per 1000 km as a suitable value for a comparison of acceleration events in the longitudinal and lateral direction, as well as for highways and other roads (see Tables 8 and 9). Although we anticipated that the relative number of acceleration events on the roads would be higher, we did not anticipate that the difference would be so large.

Table 8. Acceleration events for highways and roads for ax1000.

Total distance [km]	10,109	718	10,827
	Acceleration events		Total
ax1000	Highways	Roads	
[0.1; 0.2)	395	358	753
[0.2; 0.3)	13	21	34
[0.3; 0.4)		1	1
[0.4; 0.5)	1		1
Total	409	380	789
	Acceleration events per 1000 km		Total
ax1000	Highways	Roads	
[0.1; 0.2)	39.1	498.8	537.9
[0.2; 0.3)	1.3	29.3	30.5
[0.3; 0.4)	0.0	1.4	1.4
[0.4; 0.5)	0.1	0.0	0.1
Total	40.5	529.5	569.9

Table 9. Acceleration events for highways and roads for ay1000.

Total distance [km]	10,109	718	10,827
	Acceleration events		Total
ay1000	Highways	Roads	
[0.1; 0.2)	315	466	781
[0.2; 0.3)	31	49	80
[0.3; 0.4)	1	1	2
Total	347	516	863
	Acceleration events per 1000 km		Total
ay1000	Highways	Roads	
[0.1; 0.2)	31.2	649.3	680.5
[0.2; 0.3)	3.1	68.3	71.3
[0.3; 0.4)	0.1	1.4	1.5
Total	34.3	719.0	753.3

There are 498.8 events/1000 km on roads and 39.1 events/1000 km on highways when considering x-axis acceleration events in the interval between 0.1 g and 0.2 g, and 30.7 events/1000 km on roads, but only 1.4 events/1000 km on highways above 0.2 g. Longitudinal acceleration events higher than 0.3 g occur rarely at 1.5 event/1000 km.

There are 649.3 events/1000 km on roads and 31.2 events/1000 km on highways when considering y-axis acceleration events in the interval between 0.1 g and 0.2 g, and 69.7 events/1000 km on roads, but only 3.2 events/1000 km on highways above 0.2 g. Lateral acceleration events higher than 0.3 g occur rarely at 1.5 event/1000 km. The absolute number of acceleration events in the lateral direction is higher than in the longitudinal direction but there are more longitudinal events/1000 km on highways and more lateral events/1000 km on roads.

An acceleration of 0.2 g is considered as the minimum stability of the load unit that should withstand transport. A load unit with a stability from 0.2 g to 0.3 g could be considered as the weakest load unit. The test results show that even the weakest load units such as these can be damaged in transports, as semi-trailer vehicle combinations still reach longitudinal ax1000 and lateral ay1000 accelerations between 0.2 g and 0.3 g relatively frequently. Acceleration events higher than 0.3 g occur very rarely at 1.4 event/1000 km for roads, but only 0.1 event/1000 km for highways from our test transports.

The results are hardly comparable with other research, such as that of Ge et al. [29], with a different procedure of evaluation of acceleration events even with the same starting level of 0.1 g where the maximum average acceleration in 1000 ms as per EN12642:2016 is not used, and, therefore, the research provides higher maximum accelerations and a larger number of acceleration events because it is focused on peaks and rise times (jerks) and the maximum values are analyzed only from filtered data without evaluation times. Here, also, different vehicles are used. A two-axle delivery truck with the distance travelled of 1372 km and a two-axle tractor with a one-axle semi-trailer with the distance travelled of 892 km were used, which means that the vehicles and short-distance less-than-truckload test transports are completely different from our research of long-distance full-truckload test transports with two-axle tractors and three-axle semi-trailers of 10,827 km. Authors use the accelerometer and gyroscope for the identification of longitudinal and lateral events, while our research uses only the accelerometer for the identification of longitudinal, lateral, and vertical events based on cargo-securing standards that are based on acceleration coefficients only and do not specify how to use the gyroscope data for cargo securing. The use of an accelerometer for all three axes means that the same method is used for the identification of longitudinal, lateral, and vertical events.

Our approach is unique as it takes into consideration the in-field dynamics parameters for cargo-securing which was not considered by other researchers focused on military vehicles without evaluation times [34–37], driving tests for delivery van dynamics [38,39], pallet delivery vehicles without evaluation times [33], or unit load packaging, according EUMOS 40509, focusing on packaging and not evaluating accelerations [28].

If we compare our previous research [39] where we used the manual labeling of acceleration events for curves and roundabouts, we can confirm that our new method of automated labeling identified all analyzed acceleration events. As an example, we provide the maximum lateral acceleration of right-turn and left-turn events in Figure 8 (see also Table 5).

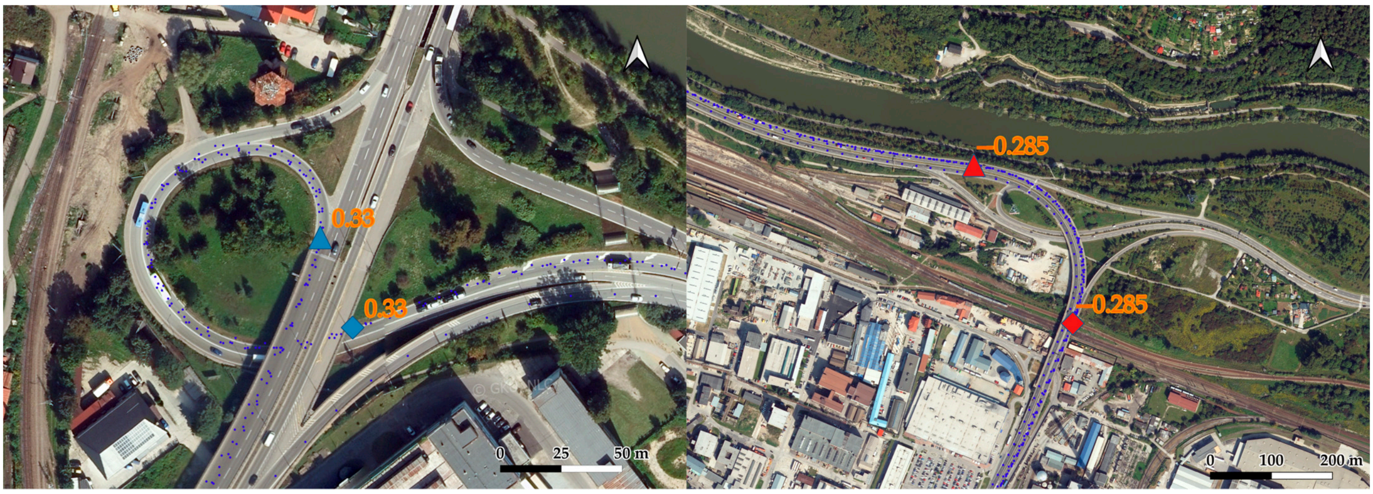

Figure 8. Maximum lateral acceleration of right-turn event of ay1000 = 0.330 g (duration 21.85 s) and left-turn event of ay1000 = −0.285 g (duration 17.7 s) with the identification of the boundaries of the event (diamond for the start and triangle for the end of the event) on an orthophoto map layer of GKÚ Bratislava, NLC.

Table 10 provides a statistical evaluation of the duration of longitudinal and lateral acceleration events with a maximum duration of 16.86 s for longitudinal events and 27.18 for lateral events.

Table 10. Statistical evaluation of duration of longitudinal and lateral acceleration events.

	Duration of Longitudinal Event [s]		Duration of Lateral Event [s]	
	>0.1 g	>0.2 g	>0.1 g	>0.2 g
minimum	1.00	1.18	1.00	3.42
mean	2.49	5.19	4.59	11.03
median	2.05	5.00	3.04	9.28
75%	2.84	6.96	5.60	14.98
80%	3.07	8.24	6.88	15.55
95%	5.79	10.36	14.29	24.47
99%	9.48	11.65	19.40	26.68
maximum	16.86	11.65	27.18	27.18

If we compare the duration of longitudinal and lateral events, we can see that lateral events are generally longer than longitudinal events. Here, the road infrastructure plays an important role because the larger the radius, the longer the duration of the lateral acceleration event. Therefore, other works of research such as [33] can obtain a longer duration of acceleration events because they are based on road infrastructure, and different vehicle dynamics and driving style (e.g., smooth or hard acceleration/braking/cornering). Because of the longer evaluation time of acceleration events, we obtained lower maximum accelerations during vehicle braking and acceleration than in [33], where 0.79% of lateral accelerations (two trucks from three, and only one from three-vehicle combinations with a one-axle semi-trailer) were above 0.40 g, but, with our different vehicle combinations (three-axle semi-trailer), we obtained zero events above 0.40 g even within the shortest evaluation time of 80 ms. We obtained lateral accelerations above 0.40 g only from filtered accelerometer data without evaluation times. If considering longitudinal accelerations, we obtained hard braking with a higher acceleration of $ax1000 = -0.492$ g and $ax80 = -0.660$ g (see Table 3) than 0.48 g in [33], but, when considering only filtered data without evaluation times, we obtained a deceleration of –0.804 g which is exceeding the designed acceleration for cargo securing, but we cannot say that this value is important for cargo securing.

Vehicle dynamics threatens the stability of load units which can cause risks to human life, reputation damage, and economic losses. Unsecured cargo poses significant risks during transport and handling. Low-stability units can cause product damage or accidents during transport and handling, leading to waste and financial losses. A sufficient load unit stability reduces product loss and avoids penalties [28,41].

There are no publicly available data about the stability of different load units. The standard prEN 17321:2021 considers a minimum stability of 0.18 g $\approx$ 0.2 g according to the expert opinions, which means that the load unit shall withstand an inclination test to 10 degrees.

We have demonstrated, through our research, that it is necessary for the load units to have a minimum stability of 0.2 g and that is because of the highest number of acceleration events in the interval of 0.1 g to 0.2 g even on highways, which are the less demanding road infrastructure

We can conclude that load units with a stability of less than 0.2 g are completely unacceptable for transport without additional securing because we obtained 70.3 acceleration events per 1000 km in the interval of 0.1 g to 0.2 g on highways, but 1148.1 events per 1000 km on other roads (see also Figures 5 and 6, top figures). We can expect such large numbers of acceleration events in this interval also during cargo handling.

If we consider that the weakest load units have a stability from 0.2 g to 0.3 g, such acceleration events still occur very frequently at 32.3 acceleration events per 1000 km on highways, but 117.3 acceleration events per 1000 km on other roads, which is still a large number of acceleration events that can damage the weakest self-standing load units (see also Figures 5 and 6, bottom figures).

There is a big difference between the number of acceleration events per 1000 km on roads and highways for all acceleration intervals, which means that there is a substantially lower probability of damaging the weak load units on highways than on other roads.

The substantial difference in the number of acceleration events on roads and highways for longitudinal acceleration is because, most of the time, the heavy goods vehicle is travelling, using cruise control, on the highway at a constant speed, which, in the European Union, is between 80–90 km/h, with very few stops. This is also because heavy goods vehicles with a gross vehicle mass over 3.5 tonnes shall be fitted with a 90 km/h speed limiter as per directive 2002/85/EC [42]. A constant speed is also possible due to the construction requirements for highways, e.g., highway interchange, and directionally divided lanes.

The difference in lateral acceleration is mainly due to the curvature of the road, where highways are designed for higher vehicle speeds and, therefore, have larger radii, which means that significantly higher speeds are required to achieve a comparable lateral acceleration than on other types of roads with a high number of curves with smaller radii, small roundabouts, T-intersections, and a large number of stops.

This leads to the conclusion that future research needs to focus on off-highway transport where lateral accelerations ay1000 higher than 0.4 g can be expected for lightly loaded semi-trailer vehicle combinations but not higher than 0.5 g. Other types of freight transport vehicles also need to be investigated, especially pallet delivery vehicles.

It should also be pointed out that, throughout the whole of the tested transports, there was no emergency hard braking to a stop, which is the worst in road transport for the load being transported and which can also be induced autonomously, where accelerations ax1000 in the range of 0.5–0.8 g can be achieved for a semi-trailer combination, with very few self-standing load units being able to withstand such accelerations. The results from heavy vehicle braking are presented in our previous research [22]. Load units with a stability of above 0.8 g, we can consider as the strongest load units for heavy vehicles in road transport. We can provide the description of an incident where the cargo is not secured in the forward direction as an example of what an emergency hard braking can cause. The vehicle combination braked autonomously, because of the traffic situation, and the loaded steel bars penetrated the semi-trailer headboard and damaged the truck cabin and engine. Fortunately, there was no damage to the cargo. Therefore, it is necessary to have the cargo always secured in the forward direction. We can agree with the Ge et al. study [33] that the acceleration profile of EUMOS 40509 is probably based on emergency braking but this must be verified by braking tests from different vehicle speeds in future research. Braking tests according to the standard EN 12642:2016 are performed with a speed of at least 35 km/h.

6. Conclusions

Tracking and monitoring goods are very important nowadays and are being increasingly emphasized. Increased visibility helps to identify potential risks, allowing for proactive measures to be taken or to prepare for claims from cargo damages. Choosing the right transport technology, including the design of appropriate precautionary measures based on the knowledge of the transport characteristics of the cargo, makes it possible to avoid unnecessary damage to the cargo and confrontations between contracting parties.

Given our results, we recommend that future research should focus on identifying acceleration events on roads other than highways. Measurements should also be made on pallet delivery vehicles and also delivery vans as they are usually fully loaded and reach higher speeds than semi-trailers. Intermodal semi-trailers should also be investigated for acceleration events in rail transport.

The parameter of the number of acceleration events per 1000 km can also be used in other future research to simply compare the results between the different vehicles, drivers, and road infrastructure, but future research should also focus on more advanced methods of comparing acceleration events and the dynamics of different vehicles and drivers on different territories, especially for delivery vehicles with multiple stops.

Author Contributions: Conceptualization, J.J. and J.K.; editing of the manuscript, J.J. and J.K.; realization, J.J.; introduction, J.J. and J.K.; literature review, J.K.; materials and methods, J.J.; data curation, J.J.; results, J.J.; writing—original draft, J.J. and J.K.; visualization, J.J.; final revision, J.J. and J.K. All authors have read and agreed to the published version of the manuscript.

Funding: The paper is an output of the European Union project NFP313011BWN6, "The implementation framework and business model of the Internet of Things, Industry 4.0 and smart transport".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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