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REDUCING RISKS STEMMING FROM THE TRANSPORT OF DANGEROUS GOODS: A CASE STUDY FROM THE CZECH REPUBLIC

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Abstract

In this research provides a comprehensive analysis of the specific risks and accident rates associated with the transport of dangerous goods within the Czech Republic. The primary aim of this research is to identify key risk factors and subsequently propose effective technical and organizational measures to minimize the occurrence of accidents and mitigate their environmental and social impacts. By utilizing and evaluating extensive data sets from the Ministry of Transport and the Police of the Czech Republic, the analysis confirms the clear dominance of road transport in the carriage of dangerous substances. Furthermore, the findings reveal a significantly higher frequency of accidents in road infrastructure compared to rail transport. The study identifies the human factor as the fundamental cause of these incidents, specifically highlighting non-compliance with safety regulations, driver inattention, and inappropriate speed. Based on these empirical findings, targeted measures are proposed, including enhanced specialized driver training, stricter monitoring of driving behavior, and the elimination of cabin distractions. In conclusion, the article emphasizes the necessity of a systematic approach and discusses the future potential of autonomous systems to effectively eliminate human error in logistics.

Keywords: freight transport; road transport; railway transport; dangerous goods; risks; accident

1. Introduction

Accidents during the transport of dangerous materials are not as frequent as personal vehicle accidents in passenger transport; however, their consequences often have a negative impact not only on human lives but also on the environment. In the recent past, serious traffic

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accidents of this kind have been documented, causing the contamination of water, soil, or air pollution [1, 2]. The subject of this study was selected traffic accidents that occurred in the Czech Republic during the transport of dangerous goods by road and rail between the years 2017 and 2022. The primary focus will be on their number, the damage caused by these accidents, and especially their causes. The data obtained from Czech institutions are processed into graphical form, based on which possible measures will be proposed that would help maintain the downward trend in the occurrence of these accidents, increase safety during transport, and contribute to the minimization of financial and environmental damage.

2. Literature Review

The transport of dangerous goods by road poses significant risks to human health, the environment, and infrastructure. In the last decade, many scientific studies have been published focusing on the identification, assessment, and mitigation of these risks. This literature review summarizes key findings from selected scientific articles indexed in the Web of Science and Scopus databases from the years 2015 to 2025.

In article [3], the authors conducted a systematic analysis of risk assessment models for the transport of dangerous materials over the last thirty years. They found that while risk assessment for road transport is well-researched, the areas of rail and combined transport remain insufficiently covered. The authors propose a new classification for monomodal transport, which could improve the understanding and management of risks in this area. The authors in [4] emphasize the need for a thorough risk analysis in the transport of dangerous goods by road. Their work focuses on identifying potential hazards and proposes methodologies for their assessment, which is crucial for accident prevention and the minimization of their impacts. In publication [5], the authors develop a dynamic risk assessment method based on monitoring data. The result is a dynamic risk map that shows the safety situation on the route in real-time. Article [6] analyzes the risks of sudden ecological disasters during transport across bridges and proposes prevention measures using Bayesian networks. Authors Lasota et al. in article [7] apply the Fault Tree Analysis (FTA) method for a graphical representation of factors leading to accidents.

To address complex road conditions and multi-factor risks in dangerous goods transportation, study [8] introduces a risk assessment model based on nine indicators spanning personnel, vehicles, and roads. The authors develop an improved hybrid algorithm by combining Particle Swarm Optimization with Artificial Fish Swarm behavior to optimize route costs. Experimental verification shows the hybrid algorithm successfully reduced total risk to 0.8863 and optimized path transportation time by 13.9%, outperforming single algorithm models.

A study [09] conducted in Lithuania identified key factors affecting safety during the transport of dangerous goods, including proper loading and unloading, the technical condition

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of the vehicle, and weather conditions. The authors recommend focusing on these areas when planning safe transport. An analysis of bitumen transport [10] was carried out in Hungary, which utilized the Failure Mode and Effect Analysis (FMEA) method to identify and assess risks. The results highlighted the importance of driver training, monitoring systems, and documentation protocols for increasing safety.

The review indicates that effective risk management in the transport of dangerous goods by road requires a comprehensive approach encompassing thorough risk assessment, comparison of transport modes, identification of key factors affecting safety, prioritization of risk factors, and the implementation of modern technologies within the framework of Smart Cities. Furthermore, it is important to consider specific conditions, such as passage through road tunnels, to achieve the highest possible level of safety. The presented article complements the analysis of risks in the road transport of dangerous goods, specifically in the conditions of the Czech Republic. It brings valuable data that is carefully analyzed and evaluated and can be beneficial in the examined area.

3. Materials and Methods

Information was primarily obtained through the analysis of expert literature and valid international agreements, in particular Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) and Regulation concerning the International Carriage of Dangerous Goods by Rail (RID). These theoretical findings were supplemented by the collection and analysis of primary statistical data from relevant institutions of the Czech Republic (Czech Statistical Office – CZSO, Ministry of Transport, Police of the Czech Republic). Data on the volume of transported commodities and dangerous cargo (CZSO) and accident statistics in rail and road transport (Ministry of Transport, Police of the Czech Republic) were collected for the period 2017–2022.

To evaluate the time trend of accident rates, a statistical significance test of the trend was performed on the annual number of accidents in road transport (ADR). Specifically, linear regression analysis (Ordinary Least Squares – OLS) was used, where the independent variable was time (year) and the dependent variable was the annual number of accidents. The goal was to quantify the rate of the downward trend and verify whether this decreasing trend is statistically significant (i.e., whether the slope coefficient is different from zero at a significance level of $\alpha = 0.05$).

Spearman's rank correlation analysis was applied to examine the monotonic relationships between accident severity, road category, and selected groups of accident causes. The analysis was performed using aggregated frequency data from ADR accident statistics for the period 2017–2022. A detailed analysis of accident causes (Figure 5) was subjected to frequency data analysis. This analysis identified the relative weight of individual cause

https://doi.org/10.14669/AM/225876

groups (e.g., "non-compliance with driving rules" constituted 25%). Subsequently, this data was used to calculate the initial risk according to formula (1), where P is the proportion of the given cause in the total number of accidents, and I is the index of existing preventive measures (initial value 1.0). This calculation served as a quantitative basis for proposing targeted preventive measures in the Discussion section, where risk reduction after the implementation of a new measure was modeled (e.g., a 20% risk reduction for the human factor based on external studies). The results of these analyses are discussed, and subsequently, proposals for measures that would contribute to greater safety in the transport of dangerous substances are defined.

4. Results

The transport of dangerous goods represents one of the important areas of freight transport. According to available data monitoring the transport of various commodities in the Czech Republic, road, rail, and to a certain extent, inland waterway transport are utilized for the carriage of dangerous goods [11, 12].

4.1. Analysis of Dangerous Goods Transport in the Czech Republic

Statistics from the CZSO [13] indicate that the largest volume of hazardous substances is transported by road freight transport, and this trend is slowly increasing (see Figure 1). It can therefore be inferred that the highest number of traffic accidents will concern road freight transport, while accidents in rail transport will be less frequent.

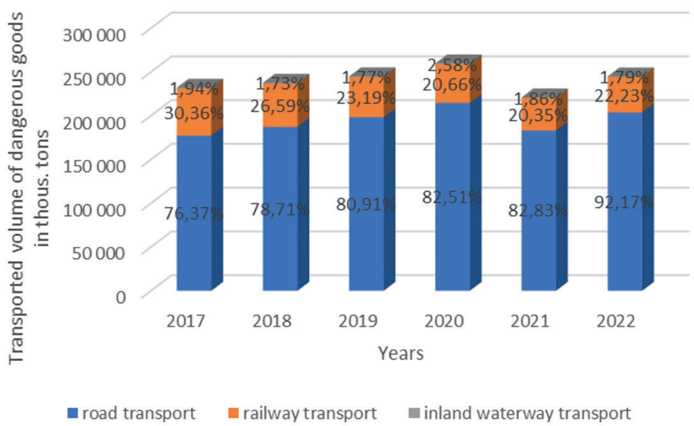

Fig. 1. Amount of dangerous goods transported by freight mode and their proportions (source: [13])

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4.2. Analysis of Accidents during the Transport of Dangerous Cargo

Rail transport can be classified as a safe and reliable mode of transport [14]. Its great advantage is the ability to transport large volumes of diverse and heavy cargo over long distances, which is positively supported by the relatively large number of railway lines in the Czech Republic [15].

Although rail transport in the Czech Republic is quite widely used for the transport of dangerous goods, accidents during their transport are very isolated, which is also evidenced by data provided by Czech institutions. Their annual frequency can be counted only in the order of single digits, and accidents in which the dangerous substance being transported is actually released are even more isolated (see in Table 1).

Tab. 1. Annual number of accidents in the transport of dangerous goods by rail (source: [16])

Railway accidents	2017	2018	2019	2020	2021	2022
Number of accidents	1	0	1	2	3	1
Including those with release of dangerous substance	0	0	1	1	1	0

Road freight transport is characterized by its flexibility and speed of transport, which is highly advantageous in the conditions of the Czech Republic, where transport distances are relatively small, mostly in the lower orders of hundreds of kilometers. Moreover, the extensive network of highways and roads in the EU and the Czech Republic allows for door-to-door transport of goods, which is valued by many customers, and provides better accessibility than rail freight transport, which is tied to timetables, tracks, and specific locations (terminals) for loading, unloading, or transshipment to another mode of transport [17].

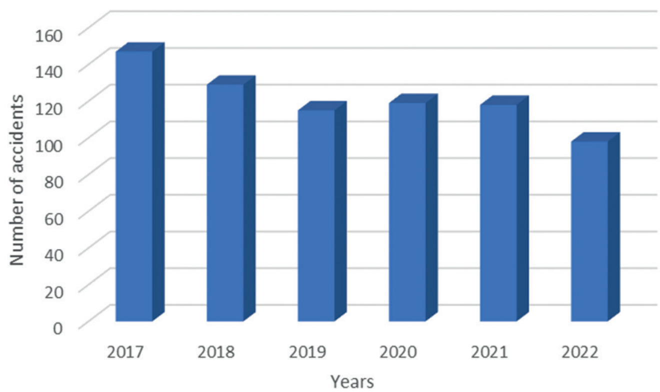

Fig. 2. Accident count in ADR transport during the observed period (source: [16])

https://doi.org/10.14669/AM/225876

Compared to rail freight transport, accidents during the transport of dangerous goods are much more frequent in road freight transport, and the annual number of such accidents is significantly higher, as evidenced by the graph in Figure 2.

At the same time, it is interesting to note that the annual number of accidents did not decrease during the coronavirus epidemic period in 2020–2021, even though there was a slight decrease in the total volume of dangerous substances transported. However, the continuing gradual year-on-year decline in accidents is a positive trend [16].

The number of injured persons resulting from ADR transport accidents annually reaches the lower tens, and such accidents do not happen each year without a loss of life. The total number of injured or fatalities in the monitored period does not differ significantly, reaching very similar numbers each year (see Figure 3).

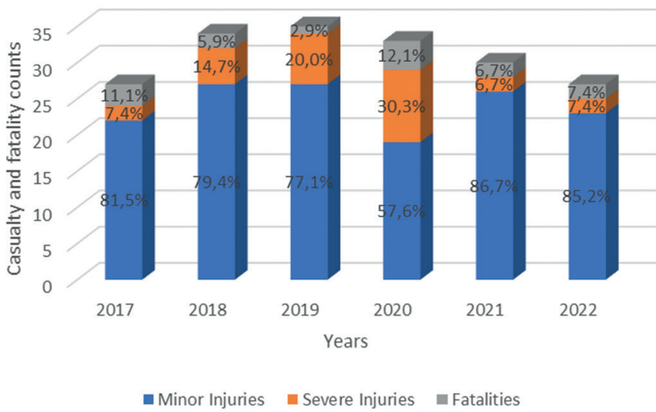

Fig. 3. Casualty and fatality counts during ADR transport in the observed period (source: [16])

In terms of the nationality of drivers involved in accidents during ADR transport, Czech drivers still prevail, although their number showed a slow decline during the monitored period. Accidents involving other nationalities also show a slight decrease, which may be due to the mitigation of demand during the coronavirus pandemic in 2020 and 2021 when anti-epidemic measures were introduced [16].

The transport of dangerous goods under ADR entails additional potential risks that can fully manifest during a traffic accident—the leakage of the dangerous substance itself. Depending on the properties of the substance in question, such accidents can result in greater property damage or permanent harm to human health [18, 19]. These types of accidents are relatively uncommon, with only a few occurring annually in the Czech Republic, as can be seen from Table 2. According to the data, these accidents result in fatalities only in very rare cases, but

https://doi.org/10.14669/AM/225876

participants almost always suffer minor injuries. The types of dangerous goods are divided in the statistics according to their common states of matter—solid, liquid, and gaseous. Among the most frequently leaked dangerous substances are liquids (petroleum products, acids, alkalis, organic solvents, etc.); in exceptional cases, they are solids. During the monitored period, there were no leaks of gaseous dangerous substances during ADR transport [16].

Tab. 2. Statistics of accidents involving the release/leak of hazardous substances (ADR) (source: [16])

Period	Number of traffic accidents	Fatalities	Seriously injured	Slightly injured	Solid	Liquid
2017	8	0	0	2	0	8
2018	7	1	2	4	1	6
2019	8	1	0	2	1	7
2020	6	0	1	4	0	6
2021	6	0	0	3	1	5
2022	4	0	1	0	0	4

In addition to harm to human health, traffic accidents during the transport of dangerous goods usually result in considerable property damage to transport infrastructure, adjacent buildings, and, above all, the vehicles themselves. The total amount of these damages thus depends on the severity of the traffic accident and other factors, such as the type and quantity of dangerous cargo transported, the location and circumstances of the accident, the extent and severity of damage to the vehicle, cargo, infrastructure, or the environment, as well as potential costs for the disposal of the leaked dangerous substance, etc. In the most exceptional cases, the total damages from such incidents can reach up to several million Czech crowns [13].

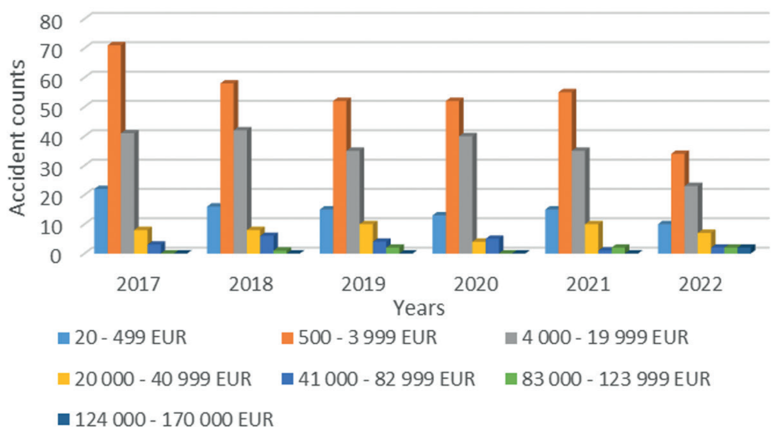

Fig. 4. Accident counts by damage extent (source: [16])

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According to the data, the final amount of damages resulting from accidents during the transport of dangerous goods most frequently falls below four thousand EUR, thus forming the most numerous group of the total number of accidents occurring in the Czech Republic (see Figure 4). The consequences of these accidents, besides minor damages, often include slight injuries which, however, usually do not require medical attention, and we can therefore label them as minor accidents. In the monitored period, this range is between 20 – 499 EUR and 500 – 3 999 EUR, with the largest number of accidents in this range occurring in 2017, which had the statistically largest number of accidents in the last 6 years. A smaller portion consists of accidents where the damage caused is in the range of 4 000 EUR to 41 999 EUR. Accidents with damages in this range can be classified as medium severity; they may involve serious personal injuries requiring medical treatment or fatalities. These accidents are less frequent, and their occurrence is also declining quite rapidly as the damages approach the imaginary limit of 41 999 EUR. The most unusual incidents are accidents with total damages exceeding 41 999 EUR, with the number of cases in this group counting only in single digits annually. Such high damages are mostly caused by damage to the vehicle, the transported goods, the effects of the transported dangerous substance that entered the surrounding area, etc. Therefore, we can label this group as severe accidents.

Traffic on roads is constantly changing dynamically, and the risk of a hazardous event is almost ubiquitous, which is especially true for unclear or treacherous sections or highly frequented transport routes [20, 21]. The most common type of road on which an accident during the transport of dangerous goods occurs is thus, according to statistics (see Table 3), Class I roads, with more than a third of all accidents in the monitored period happening on these roads [16].

Tab. 3. Accident count and proportion by road type (source: [16])

Accident location	2017 – 2022	Quotient [%]
Class I road	252	35.54
Motorway	137	19.32
Class II road	126	17.77
Local communication	96	13.54
Class III road	62	8.74
Monitored road (in selected cities/towns)	18	2.54
others	12	1.69
Junction (intersection in a city/town)	4	0.56
Special-purpose road	2	0.28
Total	709	100.00

Other types of roads where accidents commonly occur are motorways (19.3%), Class II roads (17.8%), and local roads (13.5%). According to [22], at the beginning of 2023, there were a total of 69 Class I roads in the Czech Republic, with a total length of 5,764.5 km. These transport

https://doi.org/10.14669/AM/225876

routes, as the main transport arteries connecting large cities and regional centers, have high traffic density, thus representing the most heavily used type of road in the country, and are often used for transporting dangerous commodities over long distances. Therefore, there is a high probability of accidents occurring on this type of road. The risk may also be increased by often narrow and winding roads with numerous bends or poorer quality signage or road surfaces. Class I roads often pass through smaller municipalities or towns, where the potential consequences of accidents involving dangerous cargo could cause significant damage. However, built-up areas (intravilán) should be equipped with appropriate traffic calming elements to mitigate the risks of accidents, increase driver attention, and improve the flow of traffic itself, such as roundabouts, speed bumps, or traffic lights [23].

There is a large number of causes of accidents and collisions in road transport, the occurrence of which is often decided in mere seconds. The Police of the Czech Republic records a total of 63 different causes in its database that lead to traffic accidents. However, for better representativeness of the results, all of them have been divided into several groups where different causes share similar characteristics. The results of this analysis are represented in Figure 5.

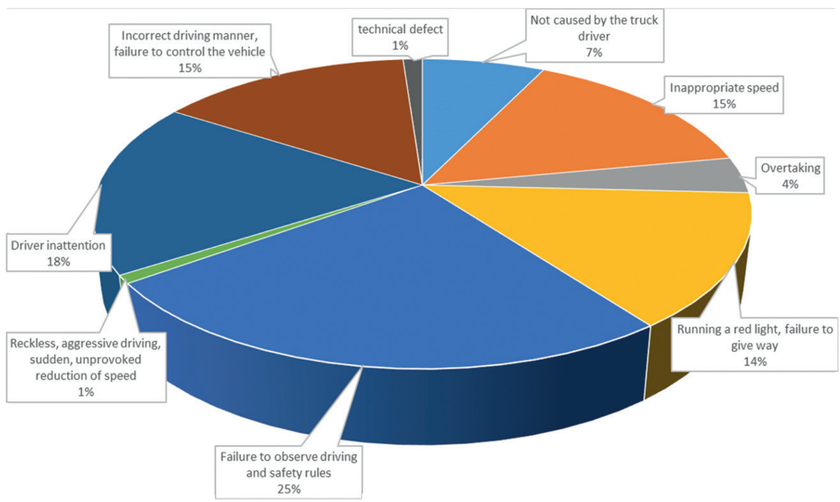

Fig. 5. Causes of accidents during ADR transport in the monitored period (source: [16])

To further examine the relationships between accident severity, accident location, and selected accident causes, Spearman's rank correlation analysis was performed using aggregated ADR accident statistics from the monitored period 2017–2022.

https://doi.org/10.14669/AM/225876

The analysis focused on the association between:

- accident severity (property damage and casualties),
- road category,
- and dominant human-related causes of accidents.

The results confirmed a moderate positive relationship between accidents caused by non-compliance with driving rules and accident severity (ρ = 0.61), indicating that violations of driving regulations were more frequently associated with accidents resulting in higher property damage or injuries. A weaker but still positive relationship was identified between inappropriate speed and accident severity (ρ = 0.48). Inattention-related accidents also showed a positive association with accident occurrence on Class I roads and motorways (ρ = 0.44).

Conversely, technical defects showed only a negligible correlation with accident severity (ρ = 0.09), which corresponds with their very low representation among the total number of recorded accidents. These findings support the assumption that the dominant risk factor in ADR transport is the human factor rather than vehicle technical condition.

Tab. 4. Spearman correlation coefficients between selected accident factors and accident severity (source: author)

Variable pair	Spearman's ρ	Interpretation
Non-compliance with driving rules × accident severity	0.61	Moderate positive correlation
Inappropriate speed × accident severity	0.48	Moderate positive correlation
Driver inattention × occurrence on Class I roads	0.44	Weak to moderate correlation
Technical defect × accident severity	0.09	Negligible correlation
Road category × property damage extent	0.52	Moderate positive correlation

The correlation analysis confirmed that human-related factors showed stronger associations with accident severity than technical defects, supporting the conclusions derived from the descriptive statistical analysis (see Table 4).

The most common group of accident causes during the transport of dangerous goods is the failure to observe driving and safety rules, which, according to statistics, accounts for almost every fourth accident. This group includes the following causes:

- driving on the wrong side of the road, entering oncoming traffic,
- overtaking/avoiding without sufficient lateral clearance,
- failure to maintain a safe distance behind a vehicle,
- improper turning or reversing,
- errors in indicating the direction of travel.

https://doi.org/10.14669/AM/225876

The second most common group of causes leading to an accident is inattention (distraction). Even a momentary glance away, a loss of overview of the situation in front of or around the driver, can lead to unpleasant and sometimes tragic events. Inattention can be caused, for example, by distraction from a mobile phone, adjusting the navigation, or simple fatigue, etc. The third position is shared by two groups: incorrect driving manner or failure to control the vehicle; and inappropriate speed.

Accidents that were not caused by the fault of the heavy goods vehicle driver represent only 7% of the total amount in the monitored period. Most often, this involves a collision with game animals that the driver could not prevent. Theoretically, accidents caused by a technical defect, which account for only 1%, could also be counted among accidents not caused by the driver. This testifies to the relatively high reliability of heavy goods vehicles and shows that the effort spent on the maintenance and technical inspection of the vehicle fleet brings positive results in preventing accidents caused by its poor condition.

To ensure compliance with prescribed road safety rules and reduce the risk of accidents, the Police of the Czech Republic carries out random inspections. During inspections of road freight vehicles transporting dangerous goods, the technical condition of the vehicles is primarily checked, such as the condition of the brakes, tires, lights, and other technical elements. Furthermore, the vehicle documents and the documents for the transported cargo are subject to inspection, as is the control of the driver's license, the technical inspection of the vehicle, and the validity of the emission certificate. For the transported cargo, checks are carried out to ensure that the dangerous goods are correctly marked and packaged, that prescribed safety standards are adhered to, and that the driver is equipped with the necessary documents regarding the transported cargo [16].

Tab. 5. ADR inspections carried out by the Police of the Czech Republic in the period 2017 – 2022 (source: [16])

Indicator	total
Transport units inspected regarding cargo content (ADR) in the Czech Republic	4151
Transport units non-compliant with ADR in the Czech Republic	422
Transport units withdrawn/detained in the Czech Republic	104
Number of infringements by risk categories – category I	232
Number of infringements by risk categories – category II	202
Number of infringements by risk categories – category III	111
Number of fines during ADR transports in the Czech Republic	310

In the period between 2017 and 2022, the Police of the Czech Republic carried out a total of 4,151 inspections of vehicles transporting dangerous goods (see Table 5). From this number, 422 cases were identified where the heavy goods vehicle was non-compliant with the ADR regulations valid in the territory of the Czech Republic. Some transport units were found

https://doi.org/10.14669/AM/225876

to be unfit for operation on roads, and thus these vehicles were banned from further travel (necessity of repair or removal). The reasons for this may include technical defects, lack of mandatory equipment, or violation of traffic rules. There were a total of 104 such cases in the monitored period.

5. Discussion

The analysis of dangerous goods transport in the Czech Republic reveals a significant disproportion in the utilization of different transport modes. Road freight transport has long dominated the territory of the Czech Republic, annually transporting over 70% of all goods. This significant disproportion can have several causes, but the most prominent among them include the geographical location and size of the Czech Republic and the flexibility provided by road transport. Road transport offers an advantage for short-distance transport, where its flexibility, speed, and accessibility excel.

The transport of dangerous goods carries the risk of hazardous incidents, sometimes resulting in significant material damage and health threats [24]. The accident analysis shows that such accidents occur very rarely in rail transport, where it is only a matter of single-digit cases per year. In contrast, accidents occur much more frequently in road freight transport, and in a much higher number per year. The higher number of accidents in road transport may be caused precisely by its higher utilization for the transport of dangerous goods, as well as the higher traffic density on roads leading to more frequent risk events and eventual accidents. According to data for the monitored period, the total material damage during accidents in road transport involving dangerous goods amounted to nearly 150 million Czech crowns, 172 people suffered minor or serious injuries, and 12 people lost their lives. Compared to rail transport, where a few accidents and a maximum of a few injuries occur annually, road transport poses much higher risks and more serious consequences; therefore, measures should primarily be aimed at reducing the accident rate in road transport.

The accident analysis reveals that the dominant risk factor is the human element (non-compliance with driving rules, inattention), which contributes to the cause of an accident in almost 60% of cases. The data from the Czech Republic thus validates international risk modeling, while specifying that in the Czech context, the problem is driver behavior (dynamic risk) rather than a technical defect (static risk, accounting for only 1% of accidents), which aligns with the trend of modern models focused on dynamic assessment [7].

The correlation analysis statistically supported the descriptive findings, confirming that human-related factors were associated with higher accident severity more strongly than technical factors.

https://doi.org/10.14669/AM/225876

The high proportion of accidents on Class I roads (35.54%) points to the fact that although the risk is associated with long transit routes, these sections often pass through municipalities and have worse geometric parameters than motorways (19.32% of accidents). This supports the risk assessment model [6], which emphasizes the necessity of taking population density and engineering structures along the route into account, especially when planning bypasses of critical sections.

Threats that can have a negative impact on human health and the environment may arise during the transport of dangerous cargo. The entire process of dangerous cargo transport is accompanied by the risk of potential threats, which must be limited. Risks can often arise even during loading operations, which include loading, transshipment (transfer), and unloading, during which situations with the potential consequence of a dangerous substance release occur [25].

The most common risk events can also include:

- damage to packaging during handling of the shipment and potential leakage of a dangerous substance,
- exceeding the maximum payload weight of the transport unit,
- violation of the prohibition on opening packages containing dangerous cargo,
- inappropriate placement of cargo,
- use of unsuitable packaging,
- insufficient securing and restraint of the shipment against movement in the cargo space,
- use of an unsuitable vehicle,
- violation of the prohibition on co-loading dangerous goods [26].

The creation of risks during the transport of dangerous goods can occur anywhere in the transport chain. Therefore, it is important that potential risks are identified in time to minimize the possibility of an accident.

The principle of determining risk probability states that its level can be reduced either by reducing the hazard (threat) or by increasing preventive measures (protection). The simplest way is to increase protection, as the hazard of transporting dangerous goods remains the same if the prescribed rules are followed; only the risk of substance leakage is reduced, not the risk of the transport vehicle being involved in an accident. From the stated causes of accidents in road freight transport, it follows that the vast majority of accidents are caused by the drivers of heavy goods vehicles. Therefore, the options that could lead to a reduction in risk and the number of accidents could be the following:

a) improvement of driver training and education: The largest share of accidents, according to the data, was caused precisely by non-compliance with driving and safety on the roads. Therefore, providing regular additional training and education focused on safe heavy goods vehicle driving, including specific rules and procedures for dangerous cargo transport, could significantly reduce the risk of an accident;

https://doi.org/10.14669/AM/225876

b) increased monitoring of driver's driving style: A large part of accidents is caused by an incorrect driving manner, failure to control the vehicle, or inappropriate speed. Using modern technologies, such as GPS (Global Positioning System), which allow the monitoring of the driver's driving style, can help identify dangerous behavior on the road, exceeding speed limits, non-compliance with traffic rules, etc.;

c) elimination of distracting elements while driving: 18% of accidents are caused by the driver not paying full attention to driving. Therefore, drivers should avoid using mobile phones, consuming food and beverages, etc., while driving. Compulsory breaks are reserved for these activities, which should serve for the driver's recovery and increased attention during the next journey;

d) improvement of the road network infrastructure: Risky areas still exist on roads where there is insufficient road surface quality, lighting, or traffic signaling. Unclear sections or sections with poor infrastructure can increase the risk of accidents; therefore, efforts should be made to eliminate these risky areas of transport roads and ensure their adequate equipment. At the same time, drivers should adhere to the given traffic signs, traffic signaling, and yield/right-of-way rules set by traffic regulations;

e) conducting regular technical inspections: Accidents caused by vehicle technical defects represent only 1% of all accidents, but many accidents can be prevented by checks carried out by the Police of the Czech Republic, which can stop a non-compliant vehicle and prohibit it from further travel. A significant number of such vehicles were uncovered during the monitored period, and it is probable that this number could continue to increase with more inspections.

According to the formula for determining risk probability [27], we can also calculate the change in risk after the introduction of a certain measure. Let's consider that the level of hazard constitutes the proportion of the selected accident cause to the total amount, and the preventive measure has an initial value of 1 under existing conditions. Then, for example, the most frequently identified cause of accidents (non-compliance with driving and safety rules), the number of which is 179 in the monitored period and the proportion of the total is 0.25, will have an initial risk level R_0:

$$R_0 = \frac{P}{I} = \frac{0.25}{1} = 0.25 \quad (1)$$

Various studies state different values for risk reduction due to quality driver training. For example, a study compiled in 2019 by the FMCSA (Federal Motor Carrier Safety Administration), a company dealing with road transport safety in the USA, found that quality driver training using driving simulators can reduce the risk of an accident in the range of 20 – 30%. If we consider the lower number in the given range and a resulting 20% reduction in risk is

https://doi.org/10.14669/AM/225876

achieved, i.e., by increasing the value of preventive measures by 0.2, the resulting value of R is then reduced:

$$R_1 = \frac{0.25}{1+0.2} = 0.208 \quad (2)$$

By this measure, we would thus achieve a reduction in the resulting risk of an accident caused by the selected reason from the original value of 25% to 20.8%. In this way, we could calculate the reduction in risk and the number of accidents for other proposed measures and causes, provided we have the value of the threat posed by the given phenomenon and the percentage influence of the measure on the given hazard, or at least an estimate of it. It must be noted that many factors further influence the risk of accidents, such as the current quality of the road infrastructure, momentary weather conditions, etc., which can complicate or change the determination of the resulting risk under certain circumstances [28].

The primary goal of prevention must be focused on the human factor. The proposed measure for improving driver training and education represents the most effective way to reduce risk, which is also confirmed by quantitative modeling, where a 20% improvement in training led to a risk reduction from the initial R_0 = 0.25 to R_1 = 0.208. It is recommended to introduce increased monitoring of driver driving style and the elimination of distracting elements, linking to the concept of a dynamic risk map and safety measures in the context of smart cities. The use of GPS and on-board telematics systems would allow a shift from passive accident recording to proactive risk management, as described in data-driven dynamic risk assessment methods.

The high number of ADR rule violations found (Table 4) suggests that even with a low number of accidents caused by a technical defect (1%), there is a significant hidden risk potential in non-compliance with regulations. Increased inspections would primarily improve static risk management (technical condition and documentation), while training and monitoring address dynamic risk (driver behavior).

When applying the proposed measures, it is necessary to take into account financial return and the multi-factorial nature of the risk [27]. Even with the implementation of all proposed steps, the risk remains, as a human is behind the wheel [28]. Future research should focus on a detailed analysis of the cost-effectiveness of individual measures. The most radical solution eliminating the human factor is autonomous transport. Although the first prototypes exist, it is necessary to perform a detailed analysis of cyber risks and system reliability in an unpredictable road environment before their widespread implementation. Shifting transport from Class I roads to rail (combined transport) for long routes could be an effective supplementary measure to minimize risk exposure in densely populated areas.

https://doi.org/10.14669/AM/225876

6. Conclusions

The transport of dangerous goods constitutes a critical and developing component of freight transport. This study confirmed that despite a decreasing accident trend, road transport (ADR) remains the main source of risk in the Czech Republic, with a significantly higher frequency of accidents, financial damage (almost 6 million EUR in the monitored period), and health injuries compared to the very safe rail transport. The analysis of road transport accidents revealed that the human factor is the dominant cause—primarily non-compliance with driving rules, inattention, and inappropriate speed. The finding that dangerous goods accidents most frequently occur on class I roads highlights the need for targeted measures for these transit, yet often inadequate, sections.

Based on the statistical analysis of key causes, specific preventive steps were proposed: improved training and increased monitoring of drivers' driving styles. Quantification showed that the introduction of quality training has the potential to reduce the initial risk of an accident by up to 20%, demonstrating the practical effectiveness of targeted prevention. At the same time, it was found that inspections by the Police of the Czech Republic reveal a significant number of vehicles non-compliant with ADR regulations, pointing to a hidden risk in static safety management.

However, new questions arise that define the future direction of research: economic effectiveness and technological risks. What is the actual financial return on the proposed measures (training, monitoring) in achieving the desired rate of accident reduction, and how best to implement advanced monitoring systems in the context of smart cities for proactive management of dangerous goods transport?

The biggest challenge remains the elimination of the unpredictability of the human factor. The future direction of transport, indicated by the development of artificial intelligence and autonomous systems, promises a fundamental removal of human error from driving. Although the first prototypes of self-driving units exist, this step will generate new challenges in the area of cybersecurity and the necessity of adapting transport infrastructure. We recommend considering a shift of part of the transport to rail (combined transport) for long distances, which will limit risk exposure on critical sections of the road network.

7. References

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