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FACULTY OF ENVIRONMENTAL SCIENCE AND ENGINEERING

PHD THESIS SUMMARY

CRITICAL INFRASTRUCTURE USED IN THE TRANSPORT OF DANGEROUS GOODS BY ROAD. ASPECTS OF ASSOCIATED RISK ANALYSIS AND SPATIAL PLANNING.

Keywords: critical infrastructure; dangerous goods; risk; spatial planning; road transport

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INTRODUCTION

In the current context of a dynamic society, which is constantly restructuring its activities, there are a number of risks in all sectors of activity. Potential actions on key aspects of society can have major effects on its ability to function, so the management of these situations by the authorities is a delicate, complex and timely process.

Significant material, human and environmental losses have been reported as a result of accidents involving the transport of hazardous substances. Recently, with the increase in the quantities and frequency of transport of explosive, corrosive, infectious, flammable, toxic or radioactive materials, there has been a worldwide increase in the number of events that have had a pronounced impact on environmental components (Fan, Chiang & Russell, 2015).

Given that any disruption to the normal operating conditions of Critical Infrastructure in the transport sector has an immediate impact on the vital functions of society, health, safety, the environment and the economic sector, as well as other Critical Infrastructures in other sectors (Radovici et al., 2016), it is considered as very important to analyze the risk at the level of these infrastructures through the prism of the different components found at local, regional or national level..

This doctoral dissertation proposes to carry out three case studies aimed at analyzing the transport process of dangerous goods at different levels of spatial expansion. These studies are based on different analysis methodologies adapted to the specifics of each case study in terms of results and availability. The study also aimed to identify Critical Infrastructures used in the transport of hazardous substances in different areas, representative at European, national, regional or local level as well as a qualitative analysis of the elements that contribute to the associated risk.

According to a report by the U.S. Federal Road Safety Administration, the losses incurred as a result of accidents involving the transportation of hazardous substances have been estimated at over $ 1 billion annually (Federal Motor Carrier Safety Administration, 2004). Thus, the high costs related to the damage caused by such events combined with the special intervention measures can be considered as additional arguments to support the need for a study dedicated to the risk management process associated with the transport of dangerous substances.

From another point of view, the Critical Infrastructure Management process is generally, or must be strongly interconnected with the Risk Management of the transport of dangerous substances, due to the fact that the effects of such an accident are not limited to its destructive aspect on the communication route (Radovici et al., 2016).

As the landscaping process in areas where dangerous goods are stored or transported has received increasing attention both in the literature and in the development of specific policies and legislation by the competent authorities, a section of this paper has been devoted to the analysis in the vicinity of the main transport routes of dangerous goods in our country.

As previously mentioned, the availability of data played an extremely important role in choosing the type and methodology of analysis, determining the following study topics materialized in the chapters of this paper:

At national level - adaptation and development of a methodology for establishing territorial compatibility between road transport routes and areas in their vicinity; the application of that methodology and the formulation of conclusions based on the results obtained.

At regional level - analysis of exposure to hazards associated with the transport of different types of goods and dangerous substances transported on a road sector that constitutes a Critical Infrastructure at national and international level; comparative analysis with an alternative route in order to establish the optimal transport route; qualitative analysis of the risk associated with an accident involving dangerous goods on the identified road sector.

At the local level - analysis of the physical effects following an accident in the transport of dangerous substances; quantitative analysis of the individual risk generated by these transports as well as the social risk.

In choosing the topic, in addition to the degree of topicality and opportunity, was taken into account the need to develop a study that brings together elements from areas that have so far been treated separately in specialized studies, so the topic also proposes a note of originality.

1 Theoretical considerations regarding the transport of dangerous goods, critical infrastructures and the associated risk

1.1 Risk - concept, components, definitions and observations

The concept of risk and risk assessment has a long and deep-rooted history in human society. However, the processes of risk assessment and management as scientific fields are quite recent, the first scientific journals, papers and conferences covering ideas and fundamental principles on how to properly assess and manage risks are not older than 30-40 years (Aven, 2016).

The following sections provide a summary of the components, principles, and methods that are the foundation of this field, while highlighting the progress of the theoretical platform and the practical models and procedures.

Natural hazards can be defined as "extreme natural phenomena whose associated consequences can cause damage to both the anthropogenic and the natural environment"(Skilodimou & Bathrellos, 2021). It is well known that hazards occur globally with random frequencies and contribute in large part to the way our planet looks.

The cause, occurrence and evolution of hazards are important and differ in size, frequency, speed and duration (Youssef et al., 2021). Moreover, the impact generated by natural or anthropogenic hazards differs depending on their location. When their consequences have a major impact on human life they are considered disasters.

As for technological hazards, they are defined as "any hazard of anthropogenic origin that may have adverse effects on humans, the natural environment and the built environment" (Skilodimou & Bathrellos, 2021). Technological threats are a wide range of modern problems and the consequences of poor management of technological processes or the design of anthropogenic elements.

In the literature, the consequences are briefly defined as the possible outcome of an undesirable event that may involve the loss or damage of items that require protection or as being determined by the potential for a hazard to cause injury, death or damage to property and the environment (Basu, 2017).

In the consequence analysis, when a succession of events (failures) may lead to a major incident, each of these events must be identified and analyzed both to determine the potential specific consequences and to identify the worst case scenario. In the case of qualitative risk analysis, it is mentioned in the literature that for each of the selected scenarios it is necessary to estimate the effects (consequences) on people, the environment and on the goods (Kajenthira, Holmes & McDonnell, 2012; Basu, 2017; Boakye et al., 2022).

With regard to risk analyzes specific to industrial processes or the transport of dangerous substances (in the case of this paper), the literature indicates that a large part is based on deterministic consequences or methods (Tugnoli, Cozzani & Landucci, 2007). In these cases, the analysis of the consequences is performed by calculating the specific physical effects for each identified scenario. The values obtained from these calculations or modeling correspond to different specific levels of consequences such as: high lethality, beginning of lethality, irreversible effects, reversible effects, destruction of concrete constructions, damage to utility networks, etc.

Vulnerability, related to natural hazards, has gained increasing attention in the literature since the 1980s, its definition being changed in the following decades.

If we refer to vulnerability from the point of view of the social sciences, we notice that a series of specialized works have focused in the last two decades on the study of individuals or groups of individuals from the perspective of medical, economic or social needs (Schröder-Butterfill & Marianti, 2006; Hutcheon & Lashewicz, 2014; Carney, 2018).

Literature studies targeting natural and technological hazards underlie the current understanding of the concept of vulnerability (Prowse, 2003). The most common formula used in the vulnerability equation used in this discipline is:

Susceptibility + Exposure + Adaptability = Vulnerability (IPCC, 2007)

"Resilience" has been used in scientific research for a very long time, however, its use in its current sense has been widely popularized with the help of studies that referred to the dynamics of ecological systems (Holling, 1973). A series of definitions have been enunciated, in several disciplines and by different entities, for a better understanding of the concept.

The transport of hazardous materials is strictly associated with safety, security and environmental issues. For this reason, the transport of hazardous materials must be treated separately from the classic transport problems but also from the technological hazards of industrial operators.

Due to the hazardous nature of the transported materials, the definition and classification of hazardous materials is regulated in most countries by law. According to the German authorities “dangerous goods are any material or object which by its very nature, characteristics or condition, when transported, poses a risk to safety or law and order, in particular to the general public ”(Holzhäuser, 2010).

Hazardous materials are generally divided into nine classes and several subclasses on the basis of specific chemical characteristics that generate risks.

The transport of dangerous substances on public roads poses a direct threat to the resident population and the environment. The truck route offers a lot of possibilities for optimization in the field of operational research. It is estimated that the amount of dangerous goods transported will increase steadily for all types of transport, but especially for road transport. The transport of dangerous goods will also continue to increase, which may in itself be an additional risk for road users, but also for the surrounding environment (nature and population). For this reason, appropriate risk analyzes should be developed for the transport of dangerous goods which make it possible to assess these risks.

1.2 General concepts of critical infrastructure protection and associated risks

Human society, like a system, develops based on the relationships between sectors and components. Also like a system, certain components that contribute to the stability and functioning of society, may be vulnerable to internal or external factors (Radovici, Muntean & Ozunu, 2015). These components, which are the most sensitive area of a system in the context of human society, are called critical infrastructures. In a broader sense we can say that critical infrastructures represent the resilience structure of a system, which provides the necessary support for the system to identify, individualize, stabilize and, of course, function (Moteff, Copeland & Fischer, 2003).

The relationship between different Critical Infrastructures provides one of their most important features: dependency. In all systems there are connections between at least two components, in our case infrastructures. If this connection is one-way, we call one infrastructure dependent on the other (Rinaldi, Peerenboom & Kelly, 2001). Unlike dependency relationships that involve unidirectional flows, in the case of interdependence relationships between two infrastructures, the state of each infrastructure is influenced or correlated with the other (Rinaldi, Peerenboom & Kelly, 2001).

1.3 Overview the theoretical synthesis

This first chapter establishes the theoretical framework used during the thesis, defining the components of risk, the notion of critical infrastructure and various associated elements. All this by making a literature overview in which a series of definitions of these terms were analyzed for a better understanding of the terminology and their use in different contexts.

Both in general and specifically in the field of critical infrastructure protection, risk assessment and management processes are based on a clearly established scientific field. In practice, these processes make important contributions to supporting decision-making.

The basic principles, theories and methods set out in this area are constantly evolving, as highlighted in this summary section of recent work and progression covers the fundamental ideas and principles on which the risk areas are based. Also, based on literature review, the signs of a revitalization on the interest for the fundamental aspects in risk assessment and management have been identified.

Regarding the concept of Critical Infrastructure, based on the synthesis of literature and analysis of legislative acts developed at various levels (national or international) it can be concluded that there is still no universally accepted definition. This aspect is highlighted by the multitude of definitions identified in the literature or legislative documents.

Similar to the areas mentioned above, the literature on the risk of transport of hazardous materials is quite extensive, most studies based on multi-criteria analysis as a starting point in risk analysis.

2 Comparative analysis of the exposure generated by road transport of dangerous goods at regional level and qualitative analysis of the risk associated with critical infrastructure

2.1 Research methodology

In choosing the area where the study will be carried out, several factors must be taken into account, such as: type of Critical Infrastructure (representative at local, regional, national or international level), type of transport of dangerous substances (road, rail, naval), the frequency of transports performed at the level of the area, the quantities transported, the exposed elements (population, economic operators, hospitals, schools, etc.) as well as the environmental factors (aquatic units, protected areas, etc.).

The risk assessment at the level of existing transport routes must be complemented by the identification and assessment of the risk of alternative routes, in order to propose (in the last part of the paper) measures to prevent potentially disruptive events and risk mitigation measures.

As the present study proposes a more specific approach in the field of critical infrastructure protection, the identification stage may prove to be extremely difficult due to the lack of a method that takes into account only objective factors. Thus, it can be appreciated that this process is rather subjective, strongly influenced by the experience of the person conducting the study and the availability of information. In order for the results of this first process not to be erroneous, and to be as objective as possible, it is proposed that the identification of critical infrastructures should be done in the spirit of regulations at national level: "An element, a system or a component thereof, located in the national territory, which is essential for maintaining the vital functions of society, health, safety, security, social or economic well-being of persons and whose disruption or destruction would have an impact significant at national level due to the inability to maintain those functions” (OUG 98/2010).

In order to establish the necessary steps for assessing the risk associated with critical infrastructure, a method developed by the United States Federal Emergency Management Agency was used as a guide. Although this method was initially used in the terrorist risk assessment on buildings (FEMA, 2005), its wide applicability allows studies to be conducted both in other areas of interest and for other risk factors.

The risk assessment process by this method is relatively simple, but in order to create an objective analysis it is necessary to know in detail the characteristics of the critical infrastructures, the dynamics, the vulnerabilities as well as the financial aspects.

Impact distance is the distance from the scene of a transport accident to a certain threshold corresponding to a potential effect (eg health, environmental contamination, material damage) caused by the release of hazardous materials. The impact area is a strip bounded by the distance of impact on each side of the transport route, between the point of origin and the point of destination of the section of route analyzed.

The factors identified and presented above must be taken into account in any analysis of the routes of transport of dangerous substances. The following factors are directly related to the definition of the area of impact of a hazardous substance spill: the types of hazardous substances transported, the amount of hazardous substances released, the climatic conditions and the characteristics of the terrain. The types of materials differ in their physical, chemical and toxicological properties. These properties, together with the conditions of temperature and pressure at the time of accidental spillage, largely determine the potential for the material to explode, catch fire, form a puddle or cloud of vapor, or disperse into the atmosphere.

Hazard maps are based on the identification of Seveso locations and road transport routes. In the case of selected scenarios, the potential exposure to hazards associated with the transport of dangerous substances shall be assessed taking into account the elements at risk in the hazardous area:

- Social factors
- Environmental factors
- Economic factors

By comparing the magnitude of hazards with the level of social and individual vulnerability, the general vulnerability index is determined. The results are then used in the development of emergency response plans and land use planning, as well as in the development of measures and procedures to reduce the consequences of disasters.

2.2 Results

2.2.1 Identification of the study area and the critical infrastructures

Annex 1 of Directive 114/2008, on the identification and designation of European Critical Infrastructures and the assessment of the need to improve their protection, refers to the transport sector as an example of a major European Critical Infrastructure sector. In this context, and based on national regulations, it can be considered that the national road network can be classified as the relevant critical infrastructure at national level. Moreover, certain roads or road sections can be considered as critical European infrastructures, as disrupting or destroying traffic would have a significant impact on at least two Member States in terms of economic, social, safety, etc.

The substances included in the analysis were: petrol, diesel, LPG, ammonia, chlorine, nitrate, sulfur dioxide, explosive materials, methanol. In practice, a much larger number of hazardous substances are transported nationwide, but the substances selected in the analysis are representative of the frequency of transport as well as the quantities transported. Only routes for the transport of hazardous substances to / from Seveso operators were considered in this study for data availability reasons.

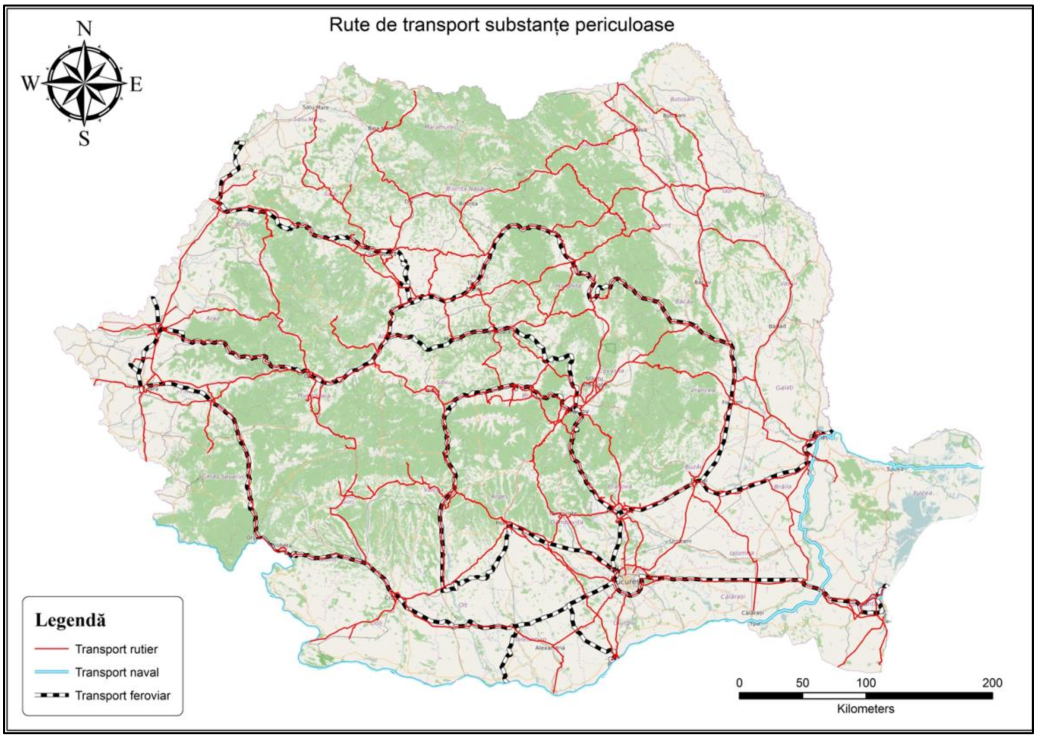

Figure 1. Hazmat transport routes in Romania

Several factors contributed to the process of choosing the study area:

- at least one nationally relevant critical infrastructure must be present in the studied area;
- regular transport of dangerous substances in the road sector in question in large enough quantities to be able to produce effects on roads or other elements in the event of an accident;
- the presence of alternative routes in the area;
- history in terms of accidents on that road sector;

Following the analysis, the road sector E81 / DN7 (Tălmaciu-Rm. Vâlcea) was identified as fulfilling the conditions mentioned above. It is known in Romania that on this road sector the frequency of accidents is very high, being also a very important connection point between Central and Southern Romania. Given the importance of this road sector and the non-existence of an alternative linking the A1 Motorway sectors between Nădlac-Sibiu and Bucharest-Pitești, the Romanian authorities have introduced in the “General Transport Master Plan” for 2017 the Pitești highway sector. -Sibiu, as to be contracted in the coming years. Thus, the two sectors (Figure 2) were selected for analysis in this study.

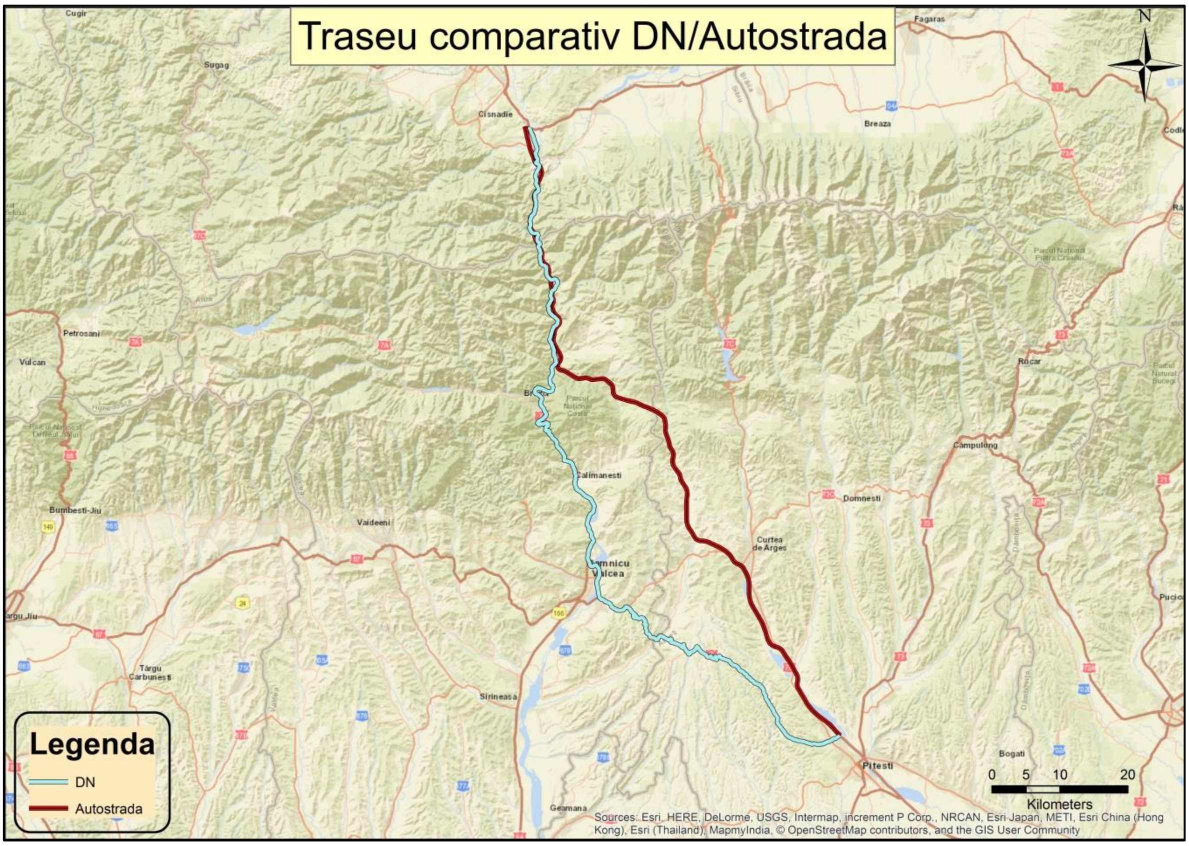

Figure 2. Road sectors selected for analysis

2.2.2 Hazard analysis

The hazard analysis identified a number of substances that could be considered relevant for impact at national level in the event of accidents during transport. The substances identified as being transported on the analyzed road sector are the following: Ammonia, ammonium nitrate, petrol, diesel, LPG, chlorine, methanol.

In order to model the possible effects that occur as a result of accidents in the process of transporting dangerous substances, the specialized software Effects was used, developed by TNO based on the models described in the literature, mainly "Yellow book" (C. van den Bosch, 2005). Similarly, the distances of occurrence of hazards and for all substances were determined, these being found in the following table:

Table 1. The distances related to the physical manifestation thresholds

	Toxic dispersion	**Fire**	**Explosion**
	Thresholds for acute	Thermal	Overpressure

		exposure				radiation [kW/m2]			[mbar]		
Hazmat	Quantity (t)	AEGL 1	AEGL 2	AEGL 3	LC 50	5	12.5	37.5	70	140	300
Ammonia	20	**8217**	2447	530	289				125	81	56
Gasoline	22					**52**	25	14.5			
Diesel	22					**40**	23	13			
Chlorine	2	**1535**	608	313	180						
Sulphur dioxide	0,4	**830**	15.6	14.2	12.2						
LPG	20								**377**	259	213
Methanol	20					**27**	21	11			
Ammonium nitrate	20								**223**	141	78

2.2.3 Hazard maps developement

For road transport routes, the processing and systematization stage consisted in identifying the routes starting from the data resulting from the RO-RISK project. They were intervened by vectorization but also by geoprocessing and editing tools. For road transport routes, where Seveso operators have not fully described the route between the point of departure and the point of arrival, the concrete route has been established on the basis of the shortest distance criterion, using roads of the highest rank, and where it was possible, bypasses of the localities. At the end of the stage all routes were integrated into the database format for processing.

2.2.4 Exposure analysis

At the level of Romania, it can be observed, analyzing the disposition of the road network, that the national and European roads transit most of the localities through their center, only in the case of big cities being bypassed belts being built. This contributes in an essential way to the exposure of the population and the elements of infrastructure characteristic of the inhabited areas. This characteristic is also found in the studied area where, largely due to geographical constraints, National Road 7 transits a number of 47 localities (Figure 3) and whose total population is 138946 inhabitants according to the 2002 population census (Institutul National de Statistica, 2002).

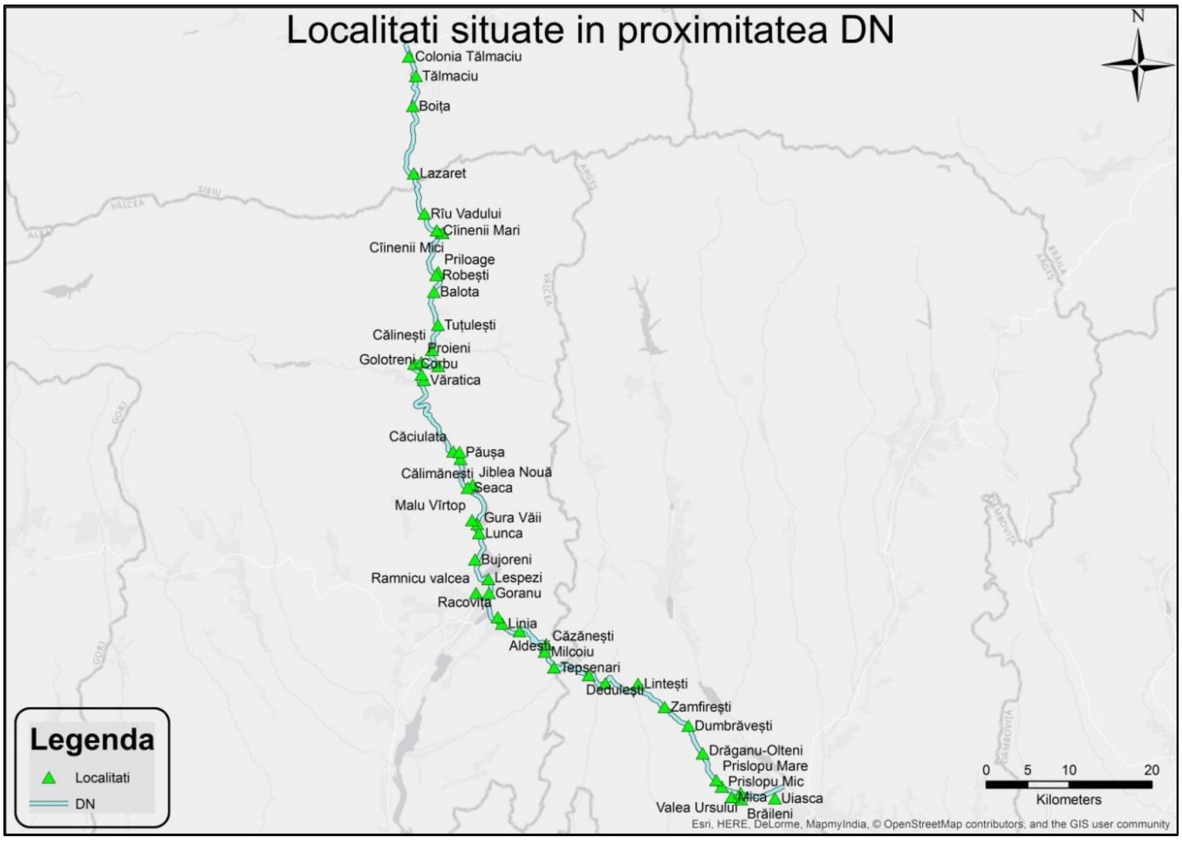

Figure 3. Localities located in the vicinity of DN 7 on the analyzed sector

Regarding the exposure of the representative infrastructure elements, some of them critical at national level, it should be mentioned that the analyzed road sector is located near the Railway Highway 201 as well as a chain of hydrotechnical facilities built on the Olt Valley.

The route of the Sibiu-Pitești Highway, as it is provided in the General Transport Master Plan, passes through the periphery of a number of 36 localities (Figure 4) with a total population of 49582 inhabitants according to the census conducted in 2002.

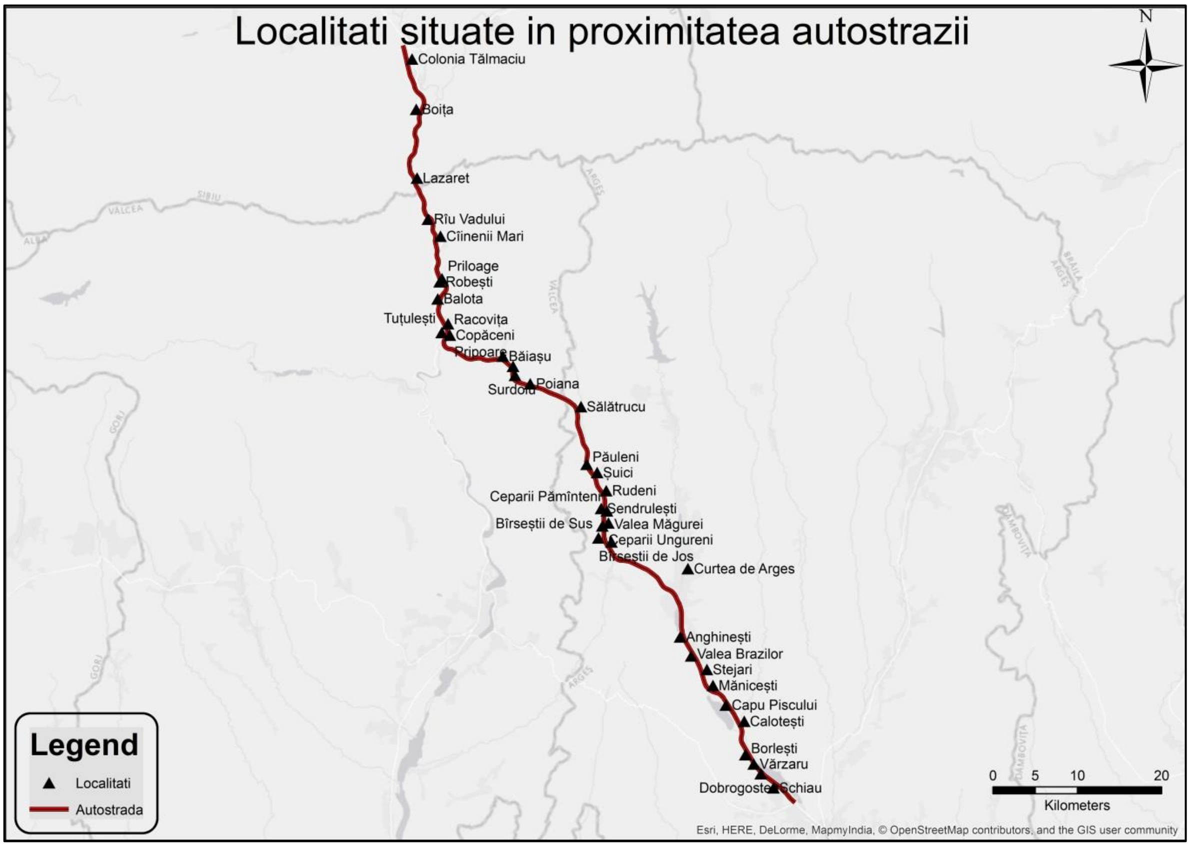

Figure 4. Localities located near the Pitești-Sibiu Highway

In the exposure analysis for the accident scenario of an ammonia tanker, anthropogenic and environmental elements located in the maximum hazardous area were identified based on land use data included in the CORINE inventory. Spatial data on the categories of elements in the hazardous area were processed by GIS techniques, resulting in exposure maps for the national road and highway sectors, as well as a numerical balance of areas by land use categories.

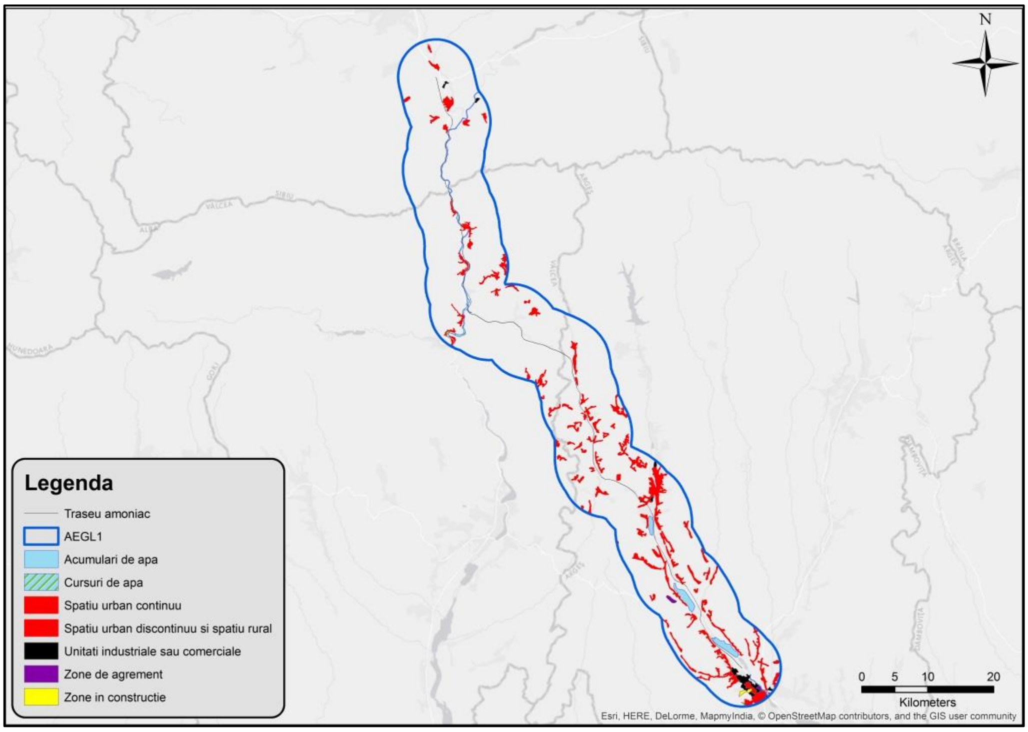

Figure 5. Highway Exposure Map (Ammonia - Toxic Dispersion)

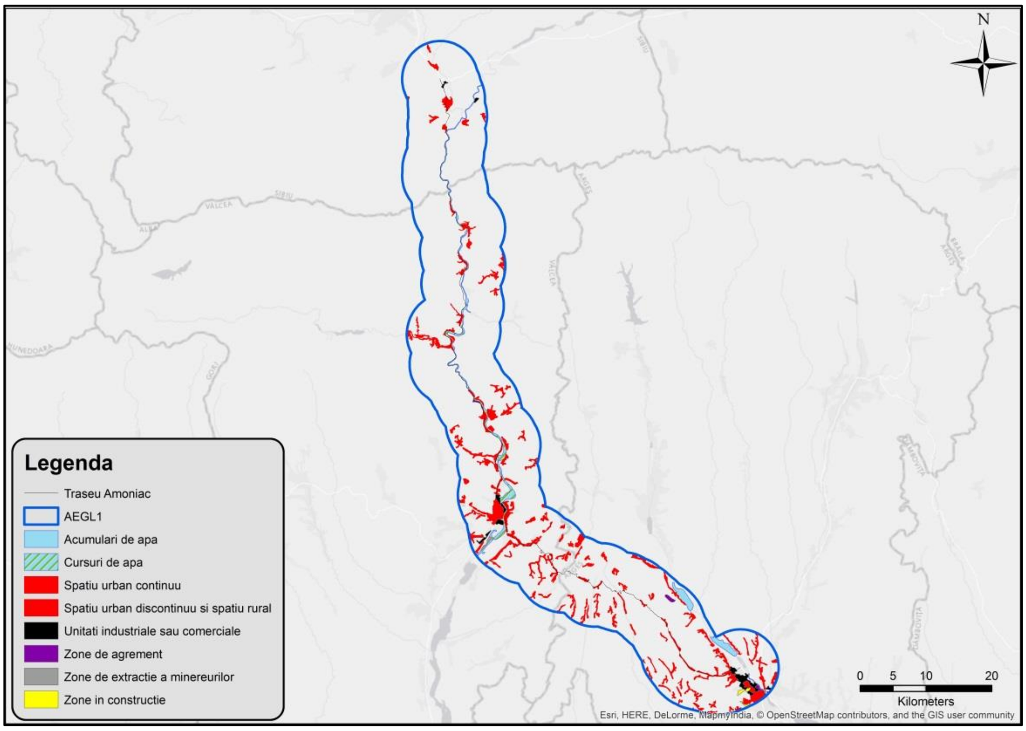

Figure 6. DN7 Exposure Map (Ammonia - Toxic Dispersion)

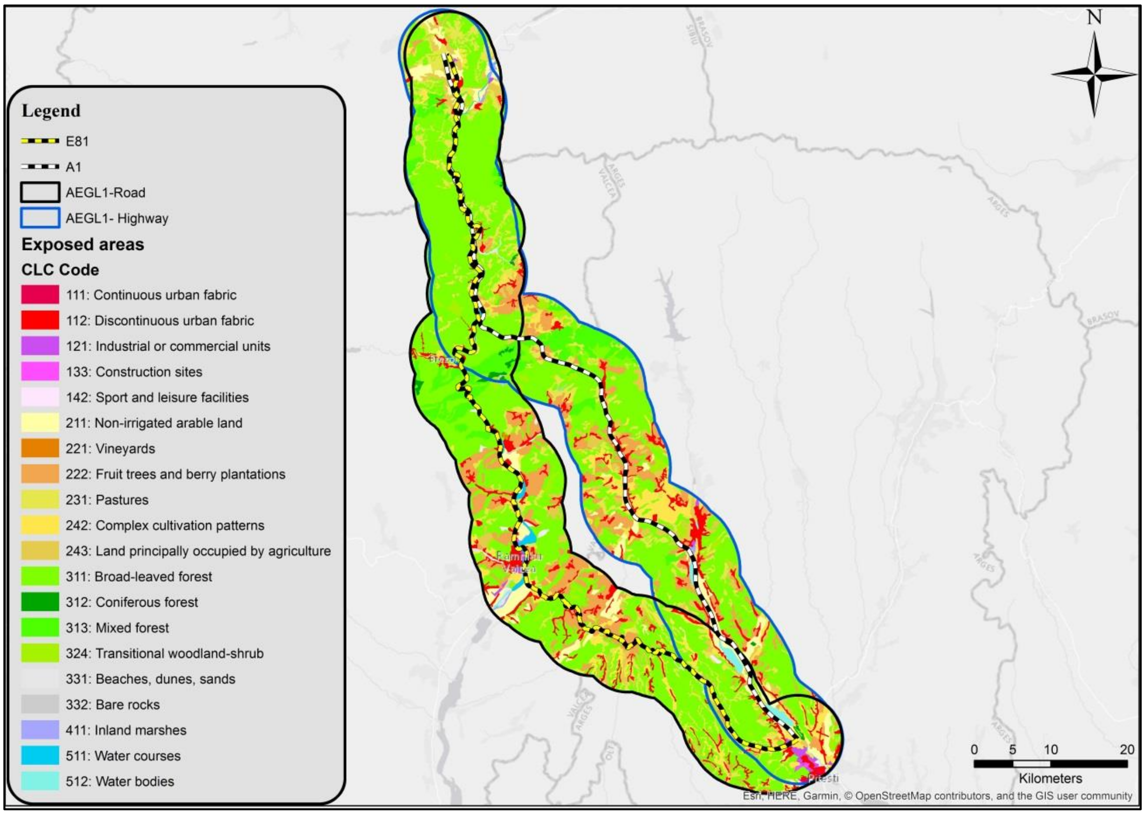

Figure 7. Comparative map of exposure to the effects of toxic ammonia dispersion

Following the comparative analysis of the exposure for the two road sectors (DN respectively Highway) it can be observed that the transport of ammonia on the highway implies a more restricted exposure of the main elements / categories of land use analyzed. Similar results were recorded in the case of exposure of protected natural areas. This type of comparative analysis was also performed for the rest of the substances transported on the two road sections.

From the analysis of the data resulting from the comparative assessment of the exposure to the transport of dangerous substances, it can be seen that the transport of dangerous substances on the highway contributes significantly to the reduction of exposure. The following graphs have been developed for a better understanding of the reduction in exposure to the transport of dangerous substances on the motorway:

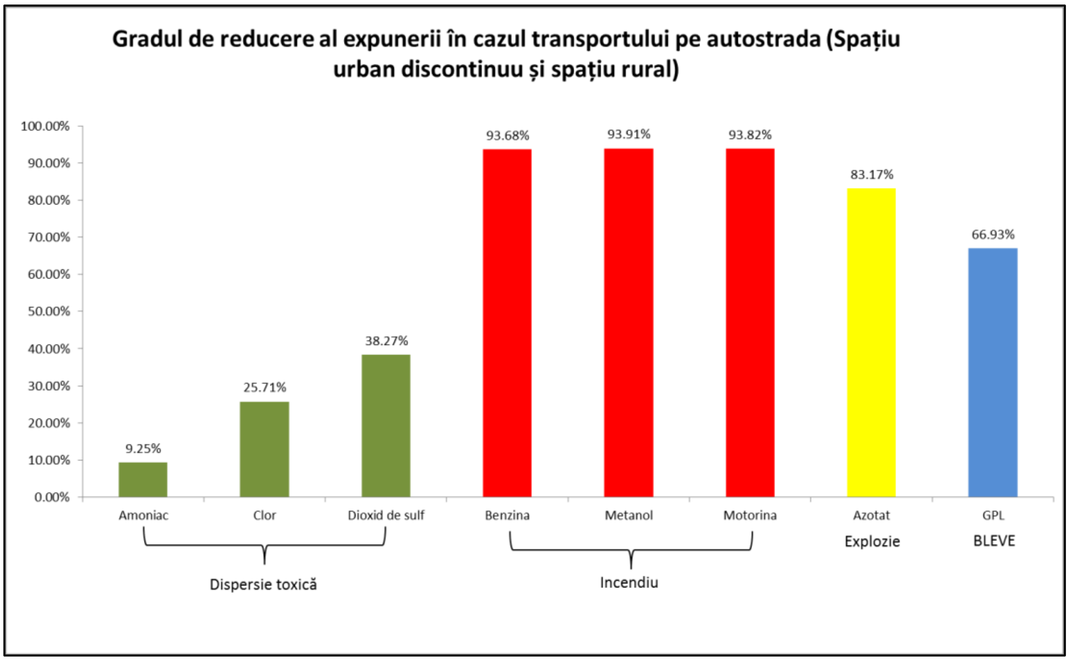

Figure 8. Exposure reduction in case of motorway transport (Discontinuous urban area and rural area)

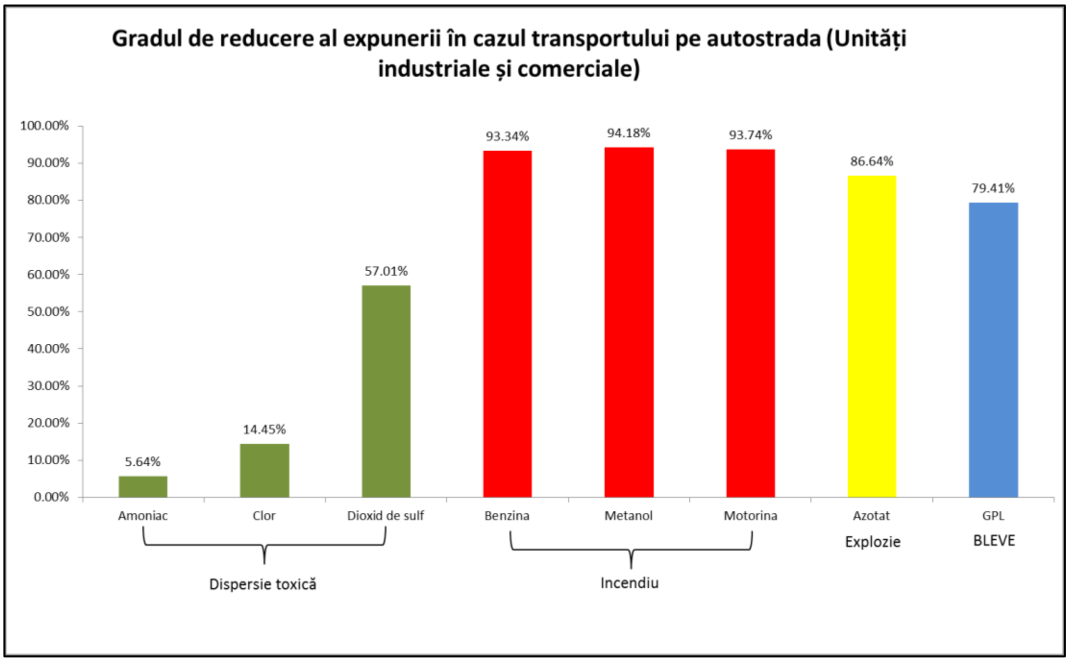

Figure 9. Exposure reduction in case of motorway transport (Industrial and commercial units)

2.2.5 Analiza calitativă a riscului asociat infrastructurilor critice utilizate în transportul de mărfuri periculoase

This last analysis process carried out at the level of the study area aims at identifying the worst possible accident scenario, on the targeted transport route, in order to establish the level of risk to which the critical infrastructure is subjected.

From a practical point of view, the prioritization of the scenarios was performed using a modified matrix for Preliminary Hazard Analysis (PHA). According to this preliminary analysis, the scenario located in the study area of this paper obtained the highest score being selected in the short list of scenarios that were analyzed in more detail.

Under these conditions, the consequences of an event (as it is foreseen in the scenario) can be manifested on several levels: the direct ones with effects on the exposed population have been mentioned before and for the prediction of the indirect consequences several bibliographic sources have been consulted.

Important subsystems of critical infrastructure have been identified in the literature, for which a certain link with road transport can be assumed, either dependent or influential (Pacinda, 2010). A total of seven such subsystems have been identified: energy, water supply, rail transport, utilities, health, communications and chemical refining (Rehak et al., 2021). The links between them were analyzed, a brief summary being presented below.

By completing a matrix with values of 1 (yes) and 0 (no), a dependency determination procedure was applied according to the performance disturbance of the subsystem or sector (S_j- where the subsystem may be disturbed; S_i- where the subsystem may disturb. Based on the sum of the values entered in the matrix, activity coefficients were calculated (1) or passivity (2) (Rehak et al., 2021). The equations for calculating the coefficients are as follows:

$$C_A \cdot S_i = \frac{\sum_{i=1}^{n} S_i}{n-1} \cdot 100\%; \qquad (1)$$

$$C_P \cdot S_i = \frac{\sum_{i=1}^{n} S_j}{n-1} \cdot 100\%. \qquad (2)$$

Table 2. Resulted values of activity and passivity coefficients (Rehak et al., 2021)

Sector	1	2	3	4	5	6	7	8
Activity coefficient	57.1	85.7	28.6	28.6	28.6	14.3	57.1	57.1
Passivity coefficient	71.4	42.9	42.9	57.1	57.1	71.4	14.3	0

Thus, in calculating the activity and passivity coefficients, it is observed that (for the specified subsystems) road transport is more dependent than influential, but disruption of activity in this sector would affect more than half of the specified subsystems.

The existence of an alternative route will have a major impact on the level of risk associated with the road transport network by reducing the pressure generated by the disruption of a component of the system. In practice, in the event of an accident on either route, it is expected that there will be only direct effects on the exposed elements (people, infrastructure) but without further disrupting the functionality of the system. The main argument in this regard is that traffic can be diverted on the alternative route without requiring considerable additional distances.

2.3 Conclusions

In this chapter, a comparative analysis of the exposure to various hazards associated with the transport of dangerous goods for a road transport route of strategic importance at national level (Olt Valley) and a route to be built (Sibiu-Pitești Highway) was performed. In this analysis, data (on routes and related quantities of dangerous goods transported by road) were taken from the draft national risk assessment (Ro-Risk). Based on these data, scenarios have been created and implicitly modeled the potential effects on infrastructure and population that may occur as a result of an accident in the process of transporting dangerous goods.

By transposing, by GIS techniques, the areas where it was established that undesirable effects may occur as a result of accidents over databases on land use, it was possible to make a quantitative analysis of the degree of exposure on each of the two routes. The results of this comparative analysis indicate a substantial reduction in exposure for the transport of dangerous goods on the motorway for all types of goods transported. It can thus be concluded that the level of risk posed by the transport of dangerous goods can be greatly reduced by the construction of the said sector of the motorway in view of the much lower level of exposure.

The qualitative risk analysis, which concerns the two transport routes, supports the conclusion previously stated by the lower score of the risk associated with the critical infrastructure (road network) in the case of the construction of the new highway sector. This scientific approach can also have practical implications, the results of the analysis being able to be included in the cost-benefit analyzes carried out within the feasibility studies developed for the future major road infrastructure objectives.

3 National analysis of territorial compatibility in the vicinity of transport routes for hazmats

Both the previous section and similar studies aimed at analyzing the road transport network used in the transport of dangerous substances in Romania (Radovici et al., 2017, 2019) they pointed out that a large part of the length of transport routes is carried out in some localities. As this aspect significantly contributes to the increase of the exposure of the population, of the anthropogenic elements and implicitly to a higher level of risk, it is necessary to carry out an analysis to show if the results of the studies are relevant. Also, in order to determine if the primary road transport network in Romania (the most used in the transport of dangerous substances) has certain peculiarities or if it has developed in a similar way to that of other European countries, it is useful to perform a comparative analysis between the primary road infrastructures of several states.

3.1 Methodology

The methodology developed for establishing the territorial compatibility for the transport of dangerous substances is based on the legislative regulations of Order no. 3710/1212/99/2017 of July 19, 2017 ”regarding the approval of the methodology for establishing the adequate distances from the potential sources of risk within the locations that fall within the provisions of Law no. 59/2016 on the control of major accident hazards in which dangerous substances are involved in land use planning and urban planning activities ”(Ordinul 3710, 2017).

This methodology aims to identify the most used routes for road transport of dangerous substances at national level, as well as the most frequently transported substances.

As the hazards associated with the transport of hazardous substances are similar to those determined by the activity of industrial operators, the requirements for determining and graphically representing impact areas along transport routes have been adapted. For this reason we can say that the method of analyzing territorial compatibility is one based on consequences and has the advantages and limitations set out in the first chapter of this paper and differs from risk-based methods (Török et al., 2020).

Unlike the provisions of Order 3710/2017 where it is mentioned as an impact area and included in the analysis the area where reversible damage occurs at the level of the exposed population, this method of analysis proposes to exclude this area. The main argument for excluding this area from the analysis is the significantly lower frequency of major accidents in the transport of dangerous substances. Since the value of the characteristic crash frequency for each scenario determines the type of compatible functional areas (the lower the frequency the more compatible areas are) the use of the area with reversible effects in the analysis would have generated compatibility in all cases.

For the designation of functional areas in the vicinity of road transport routes of dangerous substances, the European land use reference set CORINE Land Cover was used (Büttner, 2014)(CLC, 2018). Following a preliminary analysis, a number of thirty-two land use classes located in the vicinity of the transport routes were identified.

In order to establish territorial compatibility, it is necessary to assign degrees of vulnerability to each class of land use and to classify them into different types of functional areas.

The process of establishing territorial compatibility involves overlapping the impact areas in the vicinity of the transport routes of dangerous substances, resulting from the modeling of the effects, with the territorial elements entered in the Corine database and classified according to the level of vulnerability in one of the four classes. This step is followed by the use of the compatibility matrix specific to the accident frequency calculated or identified in the literature.

3.2 Results of the territorial compatibility analysis

3.2.1 Comparative analysis of the land use in the vicinity of the primary road transport infrastructure

In accordance with the steps set out in the methodology, the first step involves identifying data sources on primary road transport infrastructure at national level. The road transport infrastructure database identified and used in this analysis is OpenStreetMap, a database created as a community collaboration project to create a free editable world map (Open Street Map, 2021).

The total length of the Romanaian National Roads is 17873 km, for most of them the traffic is on one lane per direction (Sîrbu & Pătulea, 2019). According to the same authors, only in the case of 12.5% of the national roads, there is a two-way traffic.

By overlapping the primary road network (OpenStreetMap database) over a layer containing information on land use (CORINE database) it was possible to make a balance sheet that would provide information on the main categories of land use crossed (Table 3).

Table 3. The balance of the main areas crossed by the national roads in Romania by land use classes

Cod CORINE	**Nomenclature**	**Percentage of road length (%)**
112	Discontinuous urban area	34.5
211	Non-irrigated arable land	30.6
311	Hardwood forests	5.7
242	Complex agriculture	5.6
231	Pastures	5.5
121	Industrial or commercial areas	4.6

The data presented in Table 3 confirm the hypothesis that a good part of the main road transport routes in Romania cross the localities or are located in their immediate vicinity. The fact that more than a third of the length of the main roads in our country runs in built-up areas with a fairly high population density, as well as the lack of highways, generates major problems in several areas.

In order to determine whether the high share of national roads crossing localities is specific to our country or is of a general nature, a number of countries were selected for the reiteration of the analysis: Austria, Bulgaria, Spain, Croatia, Hungary, the Netherlands and Slovakia.

3.2.2 Hzamats and transport routes identification

In order to identify whether there are problems of territorial compatibility, at national level, between transport routes and their adjacent areas, a further approach to the analysis is needed in such a way as to include as much of the main road transport network as possible. Considering that road transport of flammable liquids (especially petrol and diesel) accounts for more than half of the total transport of dangerous substances at European level (Stolecka, 2020; Eurostat, 2021), the opportunity to make the territorial compatibility analysis for these transport routes has been identified.

The OpenStreetMap database also provides users with information on the locations of various points of interest, including gas stations. In order to determine whether the entire national road network can serve petrol and diesel transport, a query of the database was made in order to identify the gas stations in its vicinity, the maximum distance being 5km.

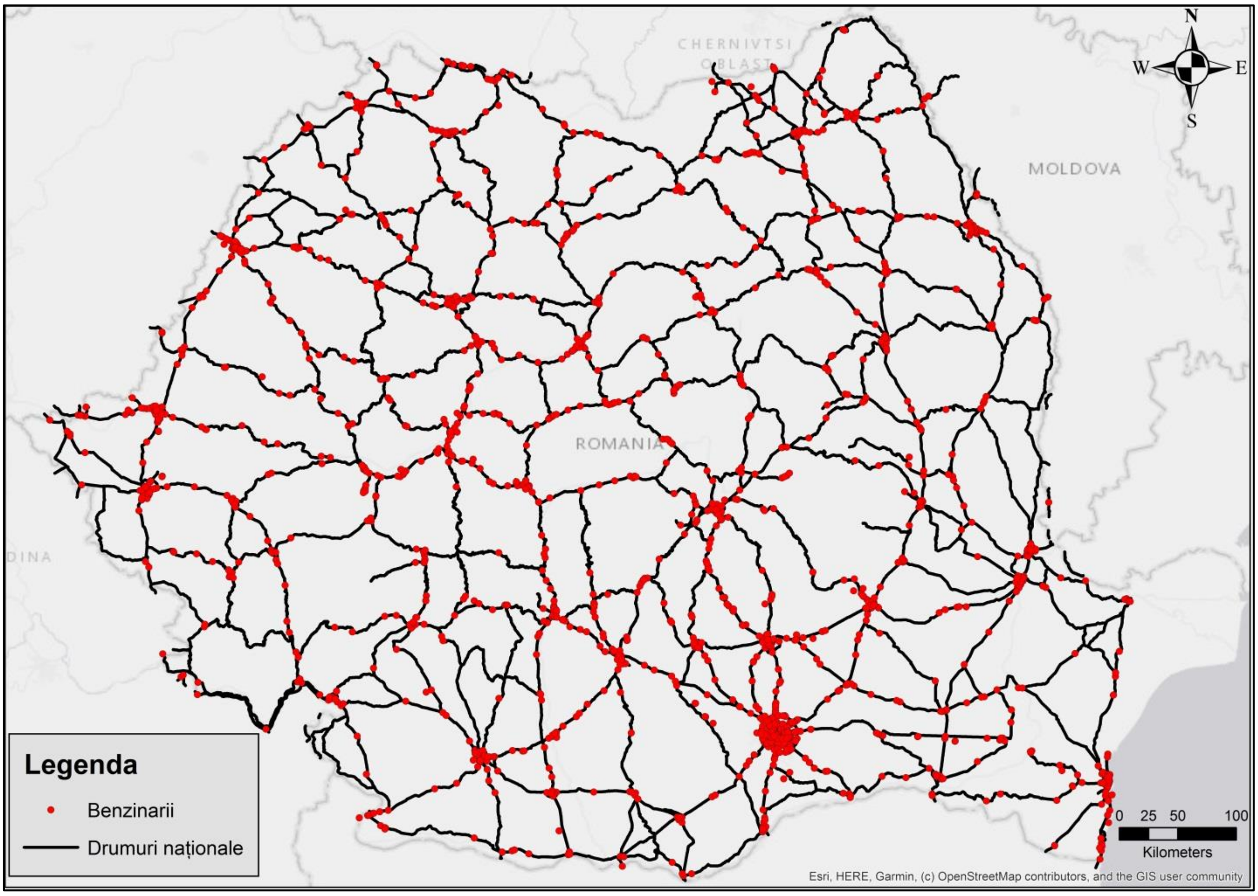

Figure 10. Spatial distribution of gas stations near national roads in Romania

Based on the analysis of the spatial distribution of gas stations in relation to the national roads in Romania, it can be stated that it has a uniform character and that almost all the main road infrastructure is used in the transport of fuels to these units.

3.2.3 Depiction of impact areas around transport routes

În urma modelărilor efectelor fizice asupra populației, pe baza celor mai rele scenarii posibile de accident ale unor autocisterne de transport motorină respectiv benzină, au rezultat valorile prezentate în Table 4 și Table 5. Scenariile analizate presupun transportul a 22 tone de combustibil.

Table 4. Threshold distances resulted from modeling of physical effects on the population following an accident in the transport of 22 tons of gasoline

Hazard type	High mortality area (m)	Mortality threshold (m)	Ireversible effects (m)
Fire	14.5	25	52
Explosion	45.2	48.2	56.3

For the transport of gasoline, the physical effects were modeled both for the thermal radiation resulting from a fire and for the overpressure caused by the explosion of the cargo.

Table 5. Threshold distances resulted from modeling of physical effects on the population following an accident in the transport of 22 tons of diesel

Hazard type	High mortality area (m)	Mortality threshold (m)	Ireversible effects (m)
Fire	13	23	40

For the transport of diesel, the physical effects of thermal radiation were modeled due to a catastrophic rupture in the tank body and the ignition of the entire amount of fuel.

3.2.4 Classification of functional areas

The European reference data set for land use CORINE Land Cover was used to designate functional areas in the vicinity of road transport routes of dangerous substances, identifying a number of thirty-two land use classes located in the vicinity of the transport routes. Each land use class was assigned a specific score for the degree of vulnerability based on the criteria described in the methodology, thus being included in one of the 4 types of functional areas.

3.2.5 Accident frequency determination

As the present case study focuses on establishing territorial compatibility for fuel road transport routes, the values available in the literature for the transport of Class 3 hazardous substances were used in the literature to determine the frequencies of major accidents: Flammable liquids and fuels (FMCSA, 2001).

The accident rate per kilometer for Class 3 road transport of dangerous substances has been calculated at $3.82*10^{-7}$. This value is used in the calculation of the accident frequency, for each analyzed route, by multiplying it by the number of kilometers of that route. Of the total number of accidents involving tankers for the transport of flammable liquids, approximately 10.2% are followed by fires and between 4.4% and 5.9% are followed by explosions. (FMCSA, 2001; Yang et al., 2010). Thus, in order to determine the frequency to be assigned to the route in the territorial compatibility analysis, the value of the route accident frequency is adjusted according to the hazard for which the analysis is performed. Basically, the value of the frequency of an accident involving a tanker carrying flammable liquids resulting in a fire is $3.9*10^{-8}$ (events / km) and the result of an explosion is $1.97*10^{-8}$ (events / km).

3.2.6 Establishing territorial compatibility

By overlapping the impact areas in the vicinity of the transport routes of hazardous substances, resulted from the modeling of effects, with the territorial elements entered in the Corine database it was possible to carry out the territorial compatibility analysis for all the national roads in Romania used in the transport of gasoline and diesel.

The resulting matrices indicate problems of territorial compatibility between the national roads in Romania and the areas in their vicinity in terms of the transport of dangerous substances - petrol and diesel in this case.

From the synthesized data we can deduce that more than a third of the lands in the areas of onset of mortality and those with high mortality are in a situation of territorial incompatibility.

In terms of territorial compatibility between the transport routes of dangerous substances and protected natural areas, the results of the analysis indicate that approximately 9.4% of all areas exposed to hazards associated with the transport of dangerous goods (gasoline and diesel) on national roads in Romania are represented by protected natural areas.

3.3 Conclusions of the territorial compatibility analysis

This chapter deals with issues related to the development and implementation of a methodology for analyzing the territorial compatibility between the transport routes of dangerous substances and the areas in their vicinity. This was initiated as a result of the results of the comparative exposure analysis (analysis carried out at regional level), which indicate that a large part of the length of transport routes is carried out in some localities - which may lead to a higher level of exposure for vulnerable elements and directly a higher level of risk.

At the level of the international scientific community as well as at the level of the governments of developed countries, there is an active concern regarding the territorial planning process in terms of the transport of dangerous substances. This concern is generally reflected in the identification of alternatives and the choice of the safest routes for the transport of dangerous substances based on several factors such as population density, type of road, type and quantity of dangerous substances transported, responsiveness, continuity of routes, effects on the economy, climatic conditions and accident history.

As Romania is still a developing state with a road infrastructure insufficiently adapted to the current volume requirements of human and freight traffic, it is insufficient and in some cases impossible for spatial planning policies in the context of the transport of dangerous substances to target only choosing the optimal routes - in many cases there are no alternatives.

Assuming that the entire national road network is used in the transport of hazardous substances, as confirmed by the results of the analysis for petrol and diesel transport, it is necessary to concentrate spatial planning activities in two directions: the development of a complex network of motorways on which most transports of dangerous substances will take place and the restriction of changing the use of land in the vicinity of national roads.

The results of the first stage of the proposed analysis certify that the national road network in Romania is largely developed in built-up areas, having the largest share of all countries analyzed. This causes a higher level of exposure of vulnerable elements to hazards associated with the transport of dangerous substances in our country. The analysis carried out at the level of historical regions showed that discontinuous urban areas occupy the first place in terms of weight, in the case of areas with national roads for all three cases, Moldova having the largest part of the national road network transiting localities.

Since at national level, in Romania, there are no legislative regulations that impose the need and the way of establishing the territorial compatibility for the transport routes of dangerous substances, in this chapter a methodology was created based on the provisions of Order no. 3710/1212/99/2017 of July 19, 2017.

Această metodologie care cuprinde patru etape majore prin definirea și reprezentarea zonelor de impact din jurul rutelor de transport, desemnarea zonelor funcționale în funcție de modul de utilizare a terenurilor, determinarea frecvenței de accident și stabilirea compatibilității teritoriale, a fost aplicată pentru rețeaua de drumuri naționale din România utilizată în transportul de benzină și motorină. Parcurgerea etapelor de analiză presupune, în mare parte, utilizarea de tehnici GIS în care sunt utilizate date de intrare de tip ”open source”, fapt ce determină repetabilitatea și reproductibilitatea rezultatelor. Acest caracter susține potențialul metodologiei propuse să fie adoptată în studii similare derulate de autorități la nivel național, regional sau local. This methodology, which comprises four major steps in defining and representing areas of impact around transport routes, designating functional areas according to land use, determining the frequency of accidents and establishing territorial compatibility, has been applied to the national road network in Romania used in the transport of petrol and diesel. The analysis steps involve, for the most part, the use of GIS techniques in which “open source” input data are used, which determines the repeatability and reproducibility of the results. This character supports the potential of the proposed methodology to be adopted in similar studies conducted by authorities at national, regional or local level.

As the method of establishing territorial compatibility was based on consequences and not on risk, the physical effects on the population and the infrastructure elements were modeled, based on the worst possible accident scenarios of some diesel and petrol tankers. Based on the distances characteristic of the physical effects, perimeters were delimited along the national roads in Romania, perimeters that were designated as impact zones. These impact areas are subsequently used in the extraction of land use data.

This chapter also included the classification of different land use classes into functional area categories based on the level of vulnerability. Thus, each of the 32 classes available in the Corine database was characterized by a low to very high level of vulnerability. Classes characterized by a higher degree of population density and land cover with anthropogenic elements were classified as having a higher level of vulnerability.

By determining the accident rate for the transport of flammable liquids and fuels, it was possible to classify fuel transport routes by frequency classes according to length. This classification in a frequency-dependent frequency class is particularly useful as it can be used in the analysis of any road transport route for fuel. The analysis of the fuel distribution infrastructure in Romania showed that most road transport of dangerous substances, involved in accidents resulting in fires, are characterized by a value of less than 10^{-5} events per year.

The territorial compatibility matrices were applied for the entire national road network in Romania in the case of diesel and petrol transports, identifying the areas where there are incompatibility problems and and share of the total exposed areas. The compatibility analysis carried out for the frequency range between 10^{-5} -10^{-6} events / year (specific for most fuel shipments) indicates that approximately 40% of the territories in the impact zone I, 35% of the territories in the impact zone II and approximately 1% of the territories in zone III are in relation to incompatibility with the process of transport of flammable substances.

These data require that the decision-makers will impose sustainable development policies that limit the exposure of vulnerable elements in the vicinity of transport routes to hazardous substances. The main way of limiting exposure is to create alternative routes (highways and local bypasses). Although the frequency and consequences of accidents involving dangerous goods vehicles do not fully justify the achievement of major infrastructure objectives, they may be important arguments in cost-benefit analysis in addition to economic profitability, limiting pollution in cities, reducing the number of accidents, etc.

Similar to the provisions governing the establishment of territorial compatibility for Seveso operators, the process of spatial planning in the vicinity of the transport routes of dangerous substances should be led by a commission composed of representatives of the structures responsible for spatial planning and urban planning within the public administration. This commission, appointed at national, regional or local level, will take over the prerogatives both to establish territorial compatibility for the existing situation and in the case of planning new roads or new constructions in the vicinity of existing routes. This commission must also monitor changes in land use in order to avoid new situations of incompatibility.

In order to reduce the level of risk associated with the transport of dangerous substances, it is proposed that a more restrictive matrix be applied for the new investment objectives developed in the vicinity of dangerous transport routes as well as for the construction of new roads / highways, as follows:

Table 6. The proposed matrix for establishing territorial compatibility for new investment objectives

Frequency (accidents / route / year)	**Impact areas**		
	Zone I- High lethality	Zone II- The beginning of lethality	Zone III-Ireversibile effects
10^{-4} -10^{-5}	A	A	A
10^{-5} -10^{-6}	A	A	AB

$< 10^{-6}$	A	AB	ABC

Also, in case the routes and developments around them, existing or future, determine incompatibilities, the authorities responsible for landscaping and urbanism as well as other designated authorities should be able to implement measures to impose technical requirements to reduce the risk.

These requirements may include limiting the speed of transport of dangerous substances, improving handling and storage methods and procedures during transport, promoting compliance with codes, regulations and safety rules, raising awareness of the public and exposed communities, and so on. Similarly, town halls in the administrative territory of which the impact areas around the transport routes of hazardous substances are located may take over the plan with the compatibility areas in the landscaping and urban planning documents and take this into account in issuing town planning certificates and of building permits.

4 Quantitative analysis of individual and social risk at the local level. Case study: LPG transport in Cluj-Napoca

Given that an urban environment can help increase the likelihood of an accident (traffic congestion being the main cause) and due tohigh population density it is very important to study all possible consequences of an accident and the risk associated with the transport of dangerous substances. It is also essential in the risk management process to have an idea of the possible effects of an accident and to optimize the response of the authorities in the given situation (Radovici et al., 2016).

As an analysis applied in the urban area covers a significantly smaller area than the previous analyzes applied at regional or national level, the parameters considered are much more specific and the level of uncertainty of the results is considerably lower.

The municipality of Cluj-Napoca was selected for analysis in order to quantitatively determine the level of risk associated with the transport of dangerous substances. This is one of the largest cities in Romania, on January 1, 2021 a number of 327927 people had a permanent residence in Cluj Napoca (Institutul Național de Statistică, 2021) determinating a density of approx 1827 loc/km^2.

The city is located at the intersection of three European roads: E60, E81 and E576. At least 31 fuel stations have been identified as operational, of which 7 also sell LPG. From the point of view of the ratio between the number of people and the number of gas stations, we can appreciate that the value of 10578 people served by a gas station is higher than other developed cities in Romania.

4.1 Methodology for assessing individual and social risk

Accidents during the transport of LPG by road can have different consequences depending on the physical circumstances of the accident but also on the intrinsic characteristics of LPG such as volatility and spontaneous combustion. (Jia et al., 2021). In addition, the storage, transport and handling conditions of LPG require strict temperature and pressure requirements, which further increases the difficulty of maintaining system security (Gong, 2006).

The scenarios identified as possible in the study area are (Radovici et al., 2016):

a) the release of LPG, as a result of a road accident, through a crack in the body of the tank or a pipe. As a result of this event, the LPG disperses into the atmosphere and creates the possibility of the occurrence of the following five scenarios.
b) LPG in the gaseous state is dispersed in the atmosphere and forms an explosive mixture of vapors in which the lower limit of explosion is reached and whose consequence is an explosion of type UVCE (Unconfined Vapor Cloud Explosion)
c) LPG vapors come into contact with an ignition source (open fire, short circuit in electrical installations damaged by the accident, etc.) resulting in a flash fire.
d) In case of ignition of LPG which is expelled with pressure from the fissure produced during the accident, the fire will be in the form of a jet of fire. The power of the jet is influenced by the pressure of the source and the exhaust section, and the direction of the fire jet will depend on the location of the fissure: horizontally, vertically or obliquely.
e) Thermal radiation resulting from a fire may create an environment conducive to the occurrence of a BLEVE event as a result of the release of the vessel containing liquid under pressure over its boiling point. (Kletz, 1990).

The scenario that has the greatest impact on the population and infrastructure is determined by a BLEVE-type explosion. This type of scenario was selected for quantitative risk analysis.

The modeling of the effects produced as a result of an accident in the transport of LPG as well as the quantitative analysis of the individual and social risk along the analyzed route, were carried out with the help of the specialized software RISKCURVES (TNO, 2017) developed by Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO).

With regard to the input parameters for the quantitative risk analysis, it is important to note that they must address the specific characteristics of the equipment included in the accident scenarios as well as the geographical location of these scenarios.

Regarding the characteristics of the LPG transport equipment (tanker) on the identified route, it is important to note that as the exact characteristics of the currently used ones are not known, it is assumed that one of the two types of tankers approved under the European Road Transport Agreement International Carriage of Dangerous Goods (ADR) is used for the transport of LPG. These two categories of tankers are differentiated by the nature of the insulation: vacuum insulated or polyurethane insulated (ADR, 2021).

The value of the accident rate was derived from statistical observations, available in the literature, for similar transports with a load of 25 tonnes and the consequences of which resulted in costs in excess of £ 10,000. (Chaplin, 2011; Health and Safety Executive (HSA), 2017).

4.2 Results and discussions

Following the modeling of the physical effects that may occur as a result of an accident in which the worst possible scenario is analyzed (BLEVE explosion of a large fraction of the total amount of LPG transported) several distances specific to the different thresholds were determined.

An area with a lethality of 1% over a distance of up to 180 meters from the center of the fireball due to the effects of thermal radiation. Threshold of 37.5 kW/m^2, related to the effects on metal structures and equipment (FEMA, 1988; NOAA Office of Response and Restoration, 2013), is located at a distance of 170 meters from the scene of the accident in the given scenario. Thermal radiation threshold with the value of 10 kW/m^2 specific to grade 3 burns (FEMA, 1988; NOAA Office of Response and Restoration, 2013), occurred to the directly exposed population, is located at a distance of 329 meters from the place of the accident in the given scenario. The distance to the overpressure threshold of 100 bar (due to the explosion of the tank body) was calculated by the modeling software as having a value of 27.5 meters, the distance up to which buildings made of reinforced concrete can suffer minor damage and multi-storey buildings in whose construction used brick, can suffer medium damages (Lees, 2012; NOAA Office of Response and Restoration, 2019).

Also due to the overpressure, at a distance of 100 meters from the place considered to be the center of the explosion, the possibility of breaking the windows of buildings and causing injuries to people inside was confirmed.

In addition to the map of physical effects caused by an accident in the transport of LPG, the RiskCurves program allowed the calculation of individual risk values and the transposition of specific isolates on a map of individual risk.

According to the isolates represented on the individual risk map, the specific values of the risk of a person being exposed to serious injury or death are generally in the range of $1*10^{-7}$-$1*10^{-8}$ events/year. A small area of the analyzed area shows individual risk values within the range events/year, the reason for this being the meteorological parameters introduced in the model and the repeated exposure. Thus, the conclusion of the quantitative analysis of the individual risk associated with the transport of LPG is that it is at an acceptable level.

The results of the quantitative analysis for social risk indicate exceedances of the acceptable threshold set as default in the RiskCurves program. This is due to the large number of people living in the immediate vicinity of the transport route.

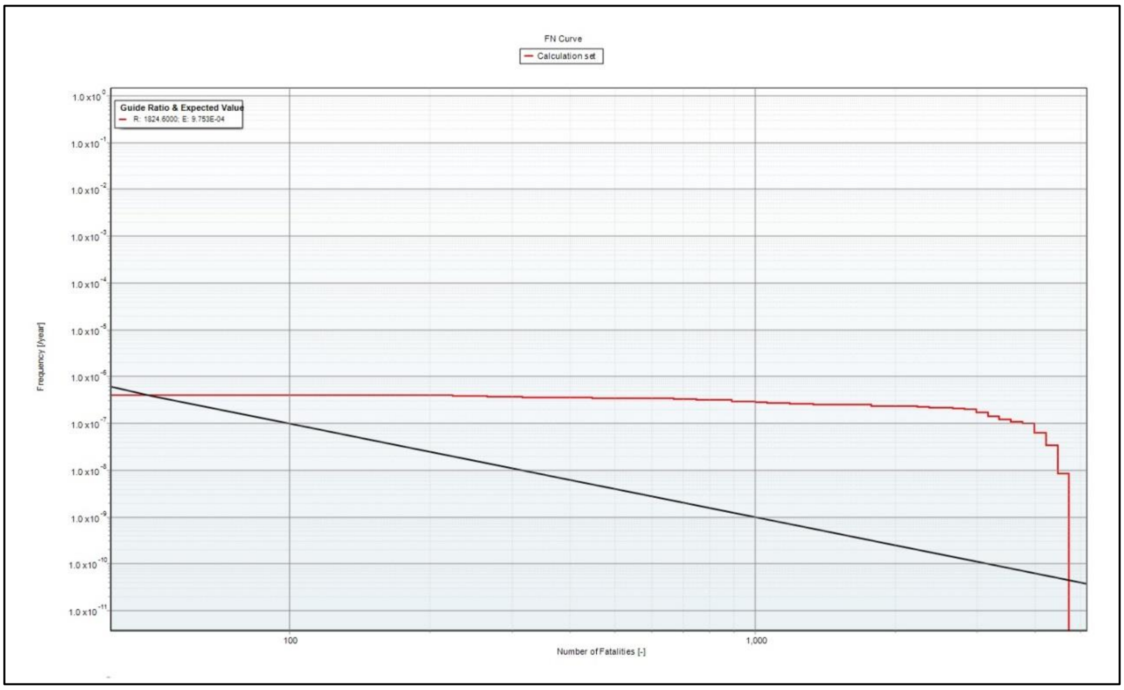

Figure 11. The results of the social risk analysis (Radovici et al., 2016)

It should be noted, however, that the results of this analysis are strongly influenced by uncertainties regarding both the spatial and temporal distribution of the number of inhabitants. For the spatial distribution, data published for the census stations from the 2002 census were taken, the number of inhabitants being extrapolated to obtain a specific value for each building in the study area.

Figure 12. Spatial distribution of the population in the study area (Radovici et al., 2016)

From the point of view of the temporal distribution of the population, as there are no clear data indicating a certain value for the fraction present in the dwelling during the day or at night in the study area, (Radovici et al., 2016) estimated that 93% of people are in the buildings in the study area during the day and 99% at night. This estimate is based on the residential nature of the study area included in the analysis.

4.3 Conclusions of the quantitative risk analysis at local level

The analysis presented in this chapter assumes a higher degree of complexity and accuracy in terms of model and data type. It is important to note, however, that this type of approach can only be useful when the analyzed area has a limited scope at the local level. A larger analysis area may introduce a high level of uncertainty into the model or the actual lack of data may make it impossible to perform the analysis. In conclusion, after the analyzes carried out at local, regional and national level, it can be said that the methods of quantitative analysis of the risk associated with the transport of dangerous goods are better suited for local research initiatives.

The individual risk values obtained in this chapter attest to the fact that its level falls within the acceptable risk limits for the scenario analyzed. However, in terms of social risk, due to the fact that the transport route takes place in a densely populated area, it has been found that the probability of having a high number of deaths per year exceeds the acceptable value.

Based on the above conclusions, it can be recommended that local authorities and decision-makers take into account in the development of spatial planning and urban planning policies measures to limit the construction of future objectives such as the one analyzed in residential areas of the city. By building these types of targets, whether they are LPG or conventional fuel distribution stations, in the peripheral areas of the city or in industrial areas, the exposure to risks associated with both the supply process and the storage and distribution process is significantly reduced.

In addition to spatial planning measures, measures can be implemented to prevent accidents on the targeted transport routes, improve response capacities, choose alternative transport routes and measures to inform the population and communicate risk effectively.

5 Final conclusions

In this doctoral thesis, a series of assessments of the risk or its components were carried out at regional, local and local level - all in the context of the threats posed by the transport of dangerous goods on both people and elements of infrastructure. Also, a central role in this research was played by the quality of Critical Infrastructure that the road network has and the importance of spatial planning in the context of limiting the consequences that may occur as a result of an accident.

Most often, in the literature but also in practice, the need to protect the infrastructures, systems and resources that are of vital importance for the society as a fundamental element in this field is highlighted. Also, a common element identified in most basic research and concept definition refers to the fact that if these systems are endangered, ie disrupted or destroyed, there will automatically be a significant impact on society in all its aspects.

By carrying out, in the first part of the paper, a comprehensive review of the literature specific to each area of interest, it was possible to determine the current level of knowledge, the methods of analysis mainly used today and general trends related to future research initiatives.

Following this approach, the opportunity was identified to address the issue of risks associated with critical infrastructure used in the transport of dangerous goods, as this issue is not widely addressed at national level. It should also be mentioned that this opportunity also derived from the involvement of the authorities and various institutions in Romania, in 2016, in a process of risk assessment relevant at national level. All these aspects contributed to a better understanding of the terminology, to the choice and adjustment of the best analysis methods suitable for the study objectives and to the identification of the data sources used in the studies.

The need to perform assessments at different levels of geographical extension (national and local) was manifested both as a result of the results obtained in the analysis of the road sector in the Olt Valley and as a result of the limitations imposed by the availability of data. The issue related to the availability of data determined the choice and adjustment of the methodologies used, a quantitative approach being feasible only in the case of risk studies conducted locally.

The results of the comparative exposure analysis for the two routes clearly indicated a lower level of exposure for vulnerable elements in the case of motorway transport. The main cause for this was the fact that DN7 crosses a series of localities or takes place in their immediate vicinity, generating a significant exposure to the population. It can be concluded that the level of risk generated by the transport of dangerous goods can be greatly reduced by the construction of the highway sector that connects Sibiu to Pitesti. The qualitative risk analysis, which concerned the two transport routes, supports the conclusion previously stated by the lower score of the risk associated with the critical infrastructure (road network) in the case of the construction of the new highway sector.

Thus, the analysis carried out at national level was intended to test the hypothesis that the entire national road network may contribute to the exposure of the population to the risks associated with the transport of dangerous goods by an insufficient degree of infrastructure development (bypasses) and by an inadequate spatial planning process.

By applying the legislative provisions regarding the territorial compatibility in the proximity of Seveso operators to the specifics of the transport of dangerous goods, it was possible to determine if there are theoretical situations (no laws in this regard) of territorial incompatibility of transport routes and adjacent areas. Given that the application of the same methodology and the analysis of the same hazards have helped to identify areas with territorial incompatibilities for fuel shipments, it can be concluded that land use planning by different authorities must also take into account the risks associated with of dangerous goods.

Although difficult to quantify from a monetary point of view, the lower exposure rate generated by the transport of dangerous goods on the highway together with the lower probability of accidents and thus the disruption of the system may be an important argument in the cost-benefit analysis.

The local risk analysis reiterated the importance of the availability of data on environmental and anthropogenic factors when using complex methodologies and quantitative analysis tools. Similar to the other approaches, this approach also highlighted inaccuracies in the processes already underway for spatial planning. The individual risk values obtained in this analysis attest to the fact that its level falls within the acceptable risk limits for the analyzed scenario. However, in terms of social risk, it has been found that the probability of having a high number of deaths per year exceeds the acceptable value.

Regarding the level of uncertainty in the studies we can say that they also vary depending on the geographical area to which the analysis was reported. The main sources of uncertainty come from the low resolution of the inventory of land use (Corine) in the case of the analysis of territorial compatibility carried out at national level. In the qualitative assessment of the risk associated with critical infrastructures used in the transport of hazardous materials, the main source of uncertainty comes from the impossibility of predicting all the indirect effects that disruption of activity in the road transport network can generate in other sectors. In the quantitative analysis of the risk at local level, the uncertainties arose from the impossibility to establish the spatial distribution of the persons from the studied area.

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