

ASSESSMENT AND MANAGEMENT OF VULNERABILITIES IN INDUSTRIAL TRANSPORT NETWORKS BASED ON DISPERSION AND EXPLOSION SIMULATIONS

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Abstract: Transporting hazardous materials poses a critical challenge to public safety and national infrastructure, amplified by intensifying industrial logistics flows. This paper analyses the risk management associated with the road transport of ammonium nitrate, a substance with a dual hazard potential: toxic and explosive. The primary objective is to evaluate vulnerabilities along two major logistical routes in Romania, on the Azomureş–Medgidia axis. The research methodology is based on simulating major accident scenarios using ALOHA and MARPLOT. Currently, Route 2 serves as the primary freight path due to lower operational costs compared to Route 1. However, results indicate this route presents a significantly higher risk level, driven by the exposure of a larger population, over 180 000 people, and the presence of critical infrastructure of major economic and logistical importance. In comparison, Route 1 reveals fewer vulnerable points, affecting approximately 125 000 people and a reduced number of strategic assets. The study concludes that, although Route 1 entails additional operational costs, its adoption minimizes human exposure and critical asset vulnerability. The research strengthens the risk assessment process and helps prevent similar incidents, providing authorities with an anticipatory planning tool that maximizes preparation and response time in the face of disasters.

Keywords: simulation, transportation, risks, explosion, dispersion

1. Introduction

The transport of hazardous materials is an essential activity in the industrial sector, with the primary purpose of moving raw materials, finished products, and waste or reaction byproducts between production facilities. Modern developments in the use of energy resources and industrial materials are driving an increase in transport, with associated risks growing exponentially, both nationally and internationally.

Hazardous substances possess various specific physicochemical properties, being flammable, corrosive, oxidizing, or toxic. These characteristics pose major risks in the event of accidents (leaks, fires, or explosions), affecting communities, the environment, and personnel in direct contact with these substances [1].

To reduce these risks, the transport of hazardous substances is regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). Its purpose is to establish rules for the classification, packaging, and labeling of chemical substances, as well as transport conditions, based on the physical and chemical properties of the materials [2]. The analysis of risks and large-scale effects generated by the transport of hazardous industrial materials is an essential step for accident prevention and for the optimal management of emergency situations should their harmful effects occur [3].

2. Risks and accidents

Risk can be defined as the probability of a negative event occurring, characterized by

the severity of its consequences for the population, the environment, infrastructure, and personnel directly exposed to the accident. These undesirable events are varied (such as leaks of hazardous substances, fires, or explosions) and are caused by factors associated with the conditions under which the accident occurred. The transport of dangerous goods across a territory generates transport risk, which manifests as an external effect in two distinct forms: the “active” form and the “passive” form.

Active risk arises when the conduct of transport activities within a territory poses a direct threat to the safety of the population (who are not directly involved in the activity), to the environment, and to the system itself. For example, in the case of the transport of dangerous goods, a spill of substances can have immediate negative effects on the areas and people in the vicinity of the accident.

Passive risk is determined by certain external events that make the conduct of transportation activities complex or even impossible. These causes are varied, including major natural disasters (earthquakes, floods), building collapses, or other catastrophic events associated. In such cases, certain areas may become isolated, cut off from the rest of the territory and difficult to access, posing an imminent threat to the safety and survival of the resident population [4].

Accidents occurring during the transport of hazardous materials can be caused by several factors acting individually or synergistically. These causes are grouped into several fundamental categories: governmental, natural, organizational, route-related, technical, and human [5].

3. Computational analysis of risk scenarios

Two complementary software programs were used to conduct the simulations, providing comprehensive information regarding risk assessment and monitoring in

the event of a chemical accident. They also help establish limits and regulations regarding the safety conditions necessary to prevent such an event.

The ALOHA application is one of the most effective tools for emergency planning and management. Its purpose is to determine the emission distances and the spread of gases and chemicals, based on location data, atmospheric conditions, and the physical and chemical properties of the materials involved in the accident [6].

MARPLOT is a geographic information system for mapping, directly interconnected with ALOHA. It integrates the calculated impact zones onto a digital map, providing a clear overview and an in-depth spatial perspective on the complexity and extent of the analyzed chemical disaster [7].

3.1 Information about places of interest

The simulation was based on real and up-to-date data, involving two key logistics hubs: the Azomureș industrial complex and the Biochem warehouse, located in Medgidia, Constanța County. Azomureș is Romania's leading producer of agricultural fertilizers, with an annual output of over 1.8 million tons [8]. Biochem Medgidia is a warehouse dedicated exclusively to chemical fertilizers, with a capacity of 9,000 tons and a strategic location relative to the Port of Constanța [9]. To determine the transport routes for chemicals between these two locations, the Google My Maps application was used, resulting in the following two main routes:

- Route 1 (R1): Azomureș (Târgu Mureș) – Brașov – Prahova Valley – Biochem (Medgidia) (distance of approximately 530 km).
- Route 2 (R2): Azomureș (Târgu Mureș) – Sibiu – Olt Valley – Biochem (Medgidia) (distance of approximately 680 km).

The primary focus of the simulations on these routes is ammonium nitrate (also known as ammonium nitrate, with the chemical formula NH_4NO_3). It is one of the

most commonly produced agricultural fertilizers by the Azomureș platform and is transported by land in massive quantities. According to ADR regulations, ammonium nitrate is classified as Class 5.1 (oxidizing substances), posing a major risk of fire and explosion under high-temperature conditions. In the event of a secondary fire, caused for example by technical malfunctions in the transport vehicle, temperatures can rapidly exceed the critical threshold of 200°C. This overheating triggers a chain decomposition reaction of ammonium nitrate, leading to the massive release of toxic gases (nitrogen oxides) and creating an imminent risk of detonation.

3.2 Identifying vulnerabilities

Vulnerable areas were selected to identify major risks along a specific route where the impact of an accident could be severe. This selection was based on the following main criteria:

- Population density: Regions with high population density have been identified, where a significant number of people could be directly exposed to a toxic cloud of NH_4NO_3 (in the event of an accidental release) [10].
- Critical infrastructure: The focus was on areas that serve as strategic logistics and transportation hubs, where a major incident would bring industrial and road traffic to a standstill.

Based on these criteria, the following points of major interest were identified along the routes analyzed:

- On R1: Sighișoara, Brașov, the Prahova Valley (Bușteni section), and the Bucharest-North Beltway.
- On R2: Alba Iulia, Sibiu, the Olt Valley (Călimănești section), Pitești (the highway section), and the Bucharest-South Beltway.
- Common points: the Cernavodă and Medgidia bridges.

3.3 Data organization

The simulations were organized based on the two established reference routes, modeling the dispersion of the toxic ammonium nitrate cloud for each selected point of interest (vulnerable area). The routes were initially marked and visualized using the Google My Maps application (Figure 1).

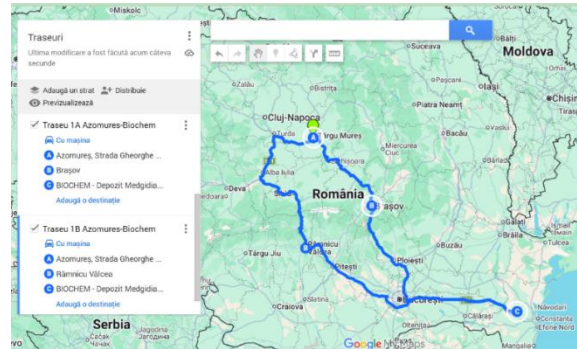


Figure 1: Creating routes of interest using the Google My Maps app

To enable a detailed spatial analysis of risk scenarios, the routes created in Google My Maps were exported as KML files and subsequently imported into the MARPLOT program [11]. This procedure allowed for the accurate transfer of geographic coordinates into the simulation system.



Figure 2: Marking vulnerable areas in Marplot

Once the routes were imported, the previously identified points of interest were marked directly on the map in MARPLOT as vulnerability zones (Figure 2). This clear visual representation is essential for delineating the areas of maximum risk along each route.

3.4. Vulnerability analysis for Route 1

For R1 (Sighișoara – Brașov – Bușteni – Bucharest North Ring Road), the next phase of the study involves modeling nitrogen dioxide dispersion at the identified critical points. The purpose of these simulations is to assess the vulnerability of urban centers and infrastructure along this major logistics route, anticipating the potential impact of a major chemical accident.

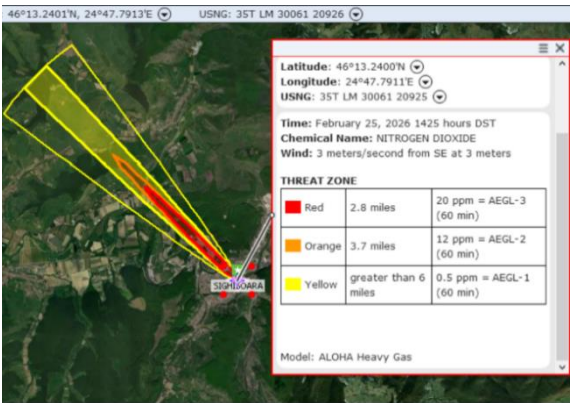


Figure 3: Illustration of the dispersion of toxic gas in Sighișoara

In Sighișoara (Figure 3), toxic gas emissions directly threaten the central-southern part of the city, affecting both residential areas and transit routes. Because nitrogen dioxide acts as a heavy gas, lethal concentrations persist at ground level within a 4.5 km radius, reducing the evacuation capacity of the exposed population and risking the blockage of transportation corridors.

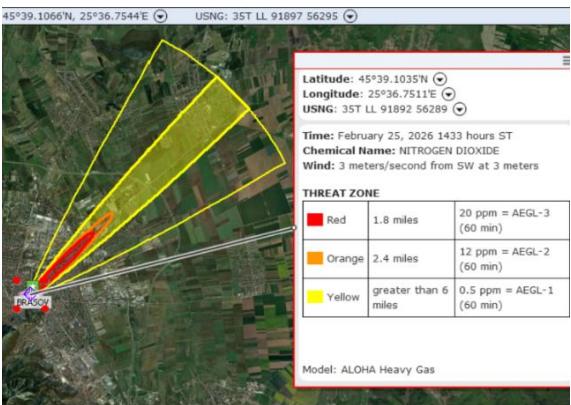


Figure 4: Illustration of the dispersion of toxic gas

In the Brașov scenario (Figure 4), the lethal cloud covers urban areas with the highest

population density, including densely populated neighborhoods (such as Tractorul) and new commercial districts, exposing a huge number of people to imminent danger. Carried by air currents from the southwest, the toxic gas maintains lethal concentrations at ground level within a radius of 2.9 km. In this area, dense urban architecture hinders the rapid dispersion of the pollutant, critically reducing the time available for a safe and organized evacuation.

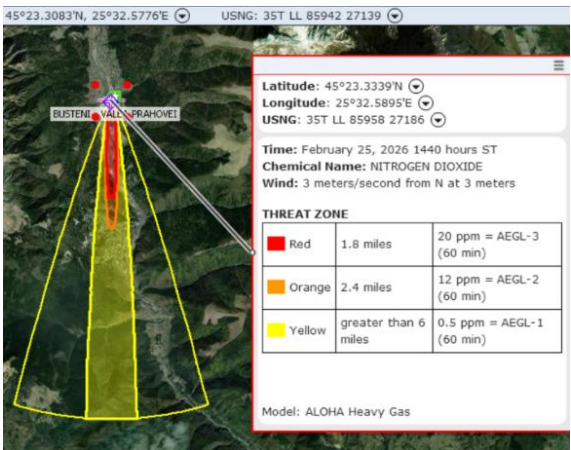


Figure 5: Illustration of the dispersion of toxic gas in the Bușteni–Prahova Valley area

In Bușteni (Figure 5), terrain and north winds channel the toxic gas south towards Sinaia, blocking DN1 and the railway. This severs all evacuation routes, creating a 2.9 km lethal zone and a 9.6 km irritating zone.

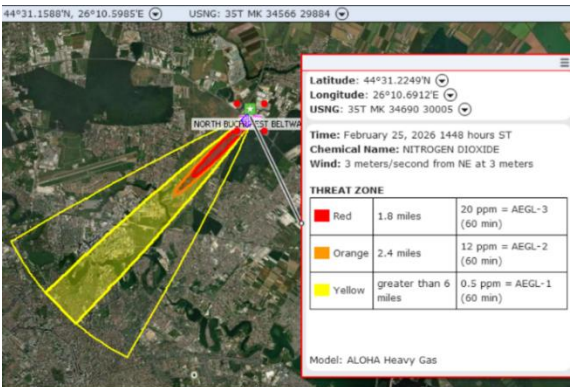


Figure 6: Illustration of toxic gas dispersion for the Bucharest-North Beltway

The Bucharest Northern Beltway (Figure 6) represents the scenario with the most devastating demographic impact.

The nitrogen dioxide plume passes directly through the business district and the Pipera residential area, spreading extensively toward Sectors 1 and 2 of the capital. Driven by the northeast wind, the heavy gas cloud maintains lethal concentrations at ground level within a 2.9 km radius, exposing a large population—both residential and

employed in business centers—to extreme danger. Analysis of nitrogen dioxide dispersion simulations for R1 (Sighișoara – Brașov – Bușteni – Bucharest Northern Beltway) highlights a major vulnerability of urban centers located along major logistics routes (Table 1).

Table 1. Demographic and infrastructure analysis for Route 1

Vulnerability	Population (people)	Critical infrastructure affected	Total toxic radius [km]
Sighișoara	10 000	DN13 (E60), the local rail network, tourist areas.	6
Brașov	40 000	Shopping areas (Coresi), northern city streets.	7
Bușteni-Prahova Valley	15 000	DN1 (complete gridlock), CFR 300 main line, tourist resorts (up to Sinaia).	9
Bucharest Northern Beltway	> 60 000	DNCB, the Pipera office district, public transportation network, hospitals in the northern area.	10

3.5 Vulnerability analysis for Route 2

For R2, which runs through the southwest and south of the country, the next phase of the analysis focuses on modeling nitrogen dioxide dispersion.

The purpose of these simulations is to assess exposure levels and potential vulnerabilities along this alternative route, with a particular focus on urban centers and critical infrastructure.

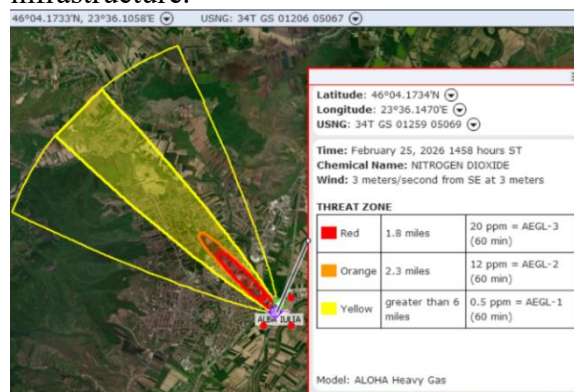


Figure 7: Illustration of the dispersion of toxic gas in Alba Iulia

Starting in Alba Iulia (Figure 7), the incident on the bypass road sends the toxic cloud

directly into the city center and the historic district, bringing the main E81 transit route to a standstill. Driven by the southeast wind, the heavy gas maintains an area with lethal concentrations at ground level within a radius of approximately 3 km, exposing a critical number of residents and tourists, while the irritating effects extend over 9.6 km to nearby towns, effectively blocking the evacuation routes.

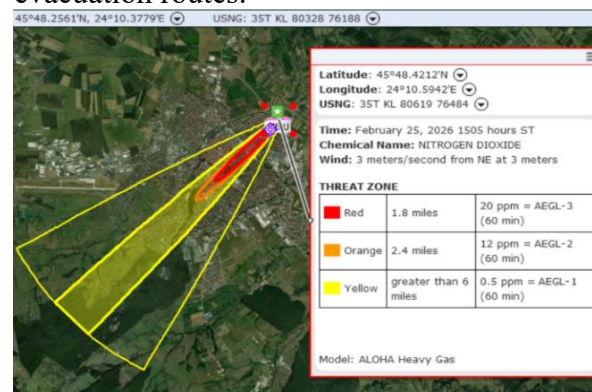


Figure 8: Illustration of the dispersion of toxic gas in Sibiu

In the Sibiu scenario (Figure 8), the plume from the A1 highway crosses the entire city

diagonally, covering the historic center and densely populated neighborhoods (Ștrand, Hipodrom, Vasile Aaron) all the way to Șelimbăr, exposing a large segment of the population. Driven by the northeast wind, the heavy gas maintains lethal concentrations at ground level within a radius of 2.9 km, while the toxic effects spread over more than 9.6 km, paralyzing both vital evacuation routes and the response capacity of emergency crews in these densely populated residential areas.

The next point, marked by the Valea Oltului-Râmnicu Vâlcea area (Figure 9), shows a complete gridlock on National Road 7, with the toxic cloud spreading across the northern part of the city, engulfing the Traian and Ostroveni neighborhoods and completely paralyzing the local infrastructure.

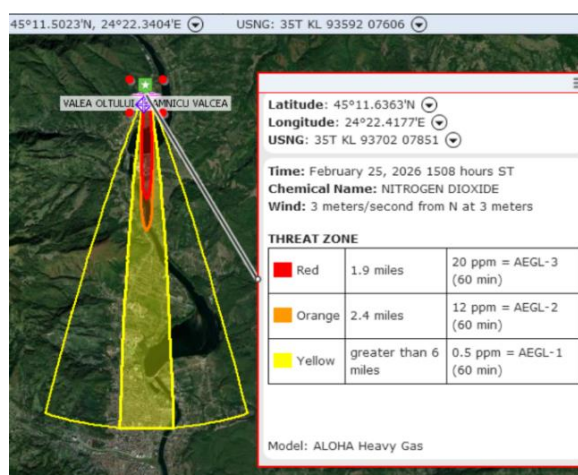


Figure 9: Illustration of the dispersion of toxic gas in the Olt Valley-Râmnicu Vâlcea area

Strictly confined by the valley's topography and carried by the north wind, the toxic gas maintains lethal concentrations at ground level over a distance of approximately 3 km, while the toxic impact zone extends to over 9.6 km, effectively eliminating any safe evacuation route for residents and people passing through the gorge.

In the Pitești area (Figure 10), the emission covers commercial areas and densely populated neighborhoods such as Găvana and Zăvoi, posing a major public health risk.

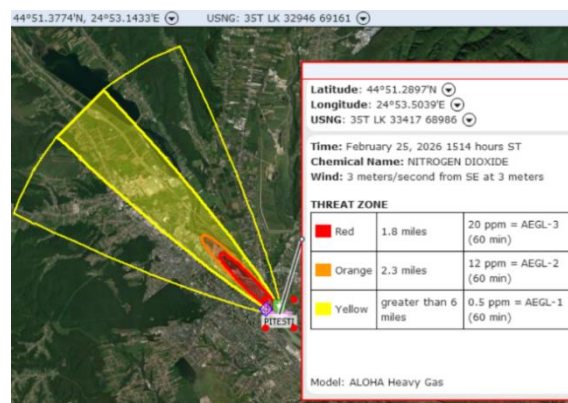


Figure 10: Illustration of toxic gas dispersion for Pitești

Carried by the southeast wind, the heavy gas cloud maintains lethal concentrations at ground level within a 2.9 km radius inside these urban centers, while the toxic effects extend more than 9.6 km to the northwest, significantly complicating evacuation and response procedures.

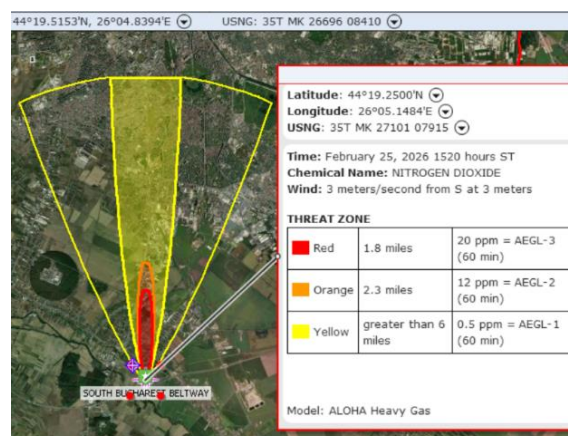


Figure 11: Illustration of toxic gas dispersion for the Bucharest-South Beltway

The incident on the Bucharest Southern Ring Road (Figure 11) represents a complex scenario, with the lethal cloud covering Sector 4 - including the neighborhoods of Progresul, Berceni, and Apărătorii Patriei - endangering tens of thousands of residents and blocking southern transportation access. Driven by southerly winds, the heavy gas maintains lethal concentrations at ground level within a 2.9 km radius directly over these densely populated residential areas, while the toxicity zone extends more than

9.6 km toward the capital's center, completely paralyzing safe evacuation routes and massively complicating response logistics. Analysis of nitrogen dioxide

dispersion simulations for R2 highlighted a number of major vulnerable points along transportation routes in the southwest and south of the country (Table 2).

Table 2. Demographic and infrastructure analysis for Route 2

Vulnerability	Population (people)	Critical infrastructure affected	Total toxic radius [km]
Alba Iulia	20 000	Route E81, the railway network, commercial and historic districts	8
Sibiu	45 000	A1 Highway, downtown, eastern industrial areas, healthcare facilities.	9
Olt Valley - Râmnicu Vâlcea	30 000	DN7 (E81) – major traffic congestion, the CFR railway network, residential areas.	8
Pitești	35 000	A1 Highway, commercial hubs (Zăvoi/Găvana), local hospitals.	9
Bucharest South Beltway	> 60 000	DNCB, neighborhoods in Sector 4 (Berceni, Apărătorii Patriei), public transportation network.	10

3.6 Analysis of the common point: Cernavodă

The simulation analysis for the Cernavodă convergence point (Figure 12) reveals a scenario involving an extreme level of risk, with a direct impact on national logistics security. In the event that the source of the toxic release is located on the bridge complex, the northwesterly wind directs the toxic cloud along the A2 highway and the course of the Danube. This dynamic creates an area with lethal concentrations over a distance of more than 8 km and a maximum gas spread reaching 12 km.

The rapid spread exposes more than 5,000 people, particularly affecting transit traffic and residents of adjacent settlements (Cochirleni, Saligny). The impact on critical infrastructure is extremely severe, simultaneously compromising the A2 Motorway, the main railway line (CFR), and navigation on the Danube River, thereby blocking the most important land and rail connection hub to the Port of Constanța.

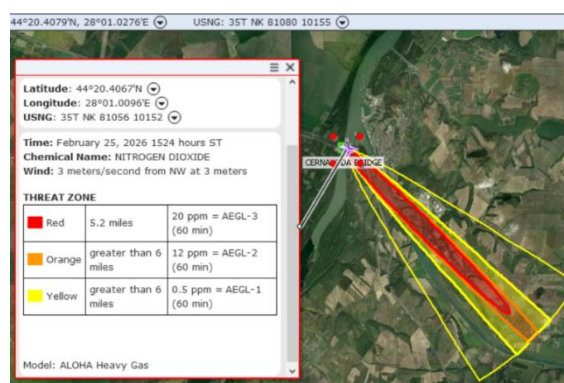


Figure 12: Illustration of the dispersion of toxic gas for the Cernavodă Bridge

3.7. Identifying critical points for both scenarios

The comparative vulnerability analysis highlights the major critical points for each logistics corridor, defined by their extreme impact on communities and infrastructure:

- R1: The highest demographic vulnerability is observed along the Bucharest North Ring Road and in the Brașov area, where the gas plume covers areas with very high population density.

- From an infrastructure standpoint, the most vulnerable point is the Bușteni resort, where road traffic would be paralyzed along the entire mountain corridor.

- R2: The Bucharest South Beltway and the city of Sibiu are areas where toxic emissions would penetrate deep into densely populated residential neighborhoods. In terms of infrastructure, the critical threshold is reached in the Olt Valley (Râmnicu Vâlcea), where the toxic cloud affects a vital logistics route with no quick detour options.

- The Cernavodă Junction: An accident at this strategic junction would cause a logistical disaster of national significance, simultaneously disrupting the A2 Motorway, the main railway line, and navigation on the Danube River toward the Port of Constanța.

Following the analysis, critical points were selected based on areas with the highest population density and fully exposed vital infrastructure, where the dispersion of the toxic cloud could have catastrophic consequences for public health.

4. Conclusions

A comparative analysis of the simulations concludes that Route 2 presents the highest overall risk level, posing major threats to both public safety and the stability of critical infrastructure. The results indicate a significantly higher risk level on this route, driven by the exposure of a larger population—over 180,000 people—and the presence of critical infrastructure of great economic and logistical importance. By comparison, Route 1 has fewer vulnerable points, affecting approximately 125,000

people and a limited number of strategic targets. The study highlights that, although Route 1 entails additional operational costs, its adoption minimizes human exposure and the vulnerability of critical assets.

Route 1 is characterized by acute demographic vulnerability concentrated in specific areas. The spread of toxic gas along the Bucharest Northern Beltway and in the Brașov metropolitan area would affect vast residential and commercial areas, resulting in a massive number of potential casualties. At the same time, on this route, the Bușteni segment represents the point of maximum infrastructure collapse, where an incident would completely paralyze road and rail traffic along the entire mountain route. Beyond the specific characteristics of each route, the junction at Cernavodă emerges as the most vulnerable strategic hub, creating a scenario of a nationwide logistical disaster. A major incident resulting in the destruction of the bridge complex would simultaneously disrupt three vital arteries: the A2 highway, the main railway line, and navigation on the Danube River. The use of simulations in risk analysis for the transport of hazardous materials is an essential tool for anticipating the effects of potential disasters. The main benefit of these analyses lies in providing a scientific basis for emergency management. On the one hand, they allow authorities to properly size emergency response teams and design safe evacuation routes by precisely delineating lethal impact zones. On the other hand, simulations offer a major preventive advantage: they provide technical justification for the need to reroute logistics away from large population centers and strategic hubs, thereby protecting human lives and national economic security.

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