Journal of Operational and Strategic Analytics
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Risk Assessment in the Transportation of Dangerous Goods: Application of ALOHA and GIS Tools in Montenegro

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Received: 09-12-2024 **Revised:** 11-30-2024 **Accepted:** 12-06-2024

Citation: M. Damjanović, A. Petrović, V. Ilić, M. Radetić, and P. Stanojević, "Risk assessment in the transportation of dangerous goods: Application of ALOHA and GIS tools in Montenegro," *J. Oper. Strateg Anal.*, vol. 2, no. 4, pp. 254–265, 2024. https://doi.org/10.56578/josa020404.

Abstract: The transportation of dangerous goods (DG) presents significant risks due to their hazardous chemical properties, which, in the event of an accident, can have detrimental effects on the environment, public health, and infrastructure. Although the transport of such materials is generally prohibited, the growing demand for DG transportation over long distances necessitates compliance with stringent international regulations (e.g., ADR, RID). In urban areas, where transport routes may intersect with residential zones, incidents involving DG can lead to severe consequences, including fatalities, environmental damage, evacuation of local populations, and disruptions to traffic. To mitigate these risks, effective risk management is essential, encompassing analysis, assessment, and reduction strategies. Risk assessment for DG transport can be conducted using various quantitative and qualitative methods, with this study employing the Areal Locations of Hazardous Atmospheres (ALOHA) software and Geographic Information System (GIS) tools for both risk evaluation and visualization. The study area is located in the capital of Montenegro, specifically within the Stari Aerodrom District. This research focuses on evaluating the potential impact of DG transport incidents in this area and the consequences of hazardous material releases in confined spaces. Three specific DGs—benzene, chlorine, and methane—are considered, each presenting distinct environmental, health, and property-related risks. Chlorine is selected as the worst-case scenario, with its impact radius extending approximately 10 km from the release point. The primary objective of this study is to provide a comprehensive assessment of the risks associated with DG transportation, highlighting the importance of safety improvements and effective emergency response strategies. The findings underscore the need for enhanced safety measures during transport and the development of more robust emergency management frameworks for DG-related incidents.

Keywords: Dangerous goods; Risk assessment; Risk management; Case study; ALOHA software

1 Introduction

The economy constitutes a crucial component of every society, with its development primarily hinging on the transport sector, which facilitates accelerated growth and fulfills the burgeoning needs of society. Beyond the primary goal of economic advancement, it is imperative to ensure clean air and a healthy community, achievable through the establishment of sustainable transportation. Sustainable transport encompasses considerations of societal, ecological, and climatic impacts. The sustainability of transport can be evaluated by the efficiency and effectiveness of transport systems and their impact on the climate and the environment. With the progression of the global economy, there is an increasing demand for the transport of DG. In the event of an incident or accident, DG can cause harm to individuals, the environment, and property (e.g., explosions, fires, poisoning, etc.). These substances are typically not utilized at the site of production but are transported over long distances. DG are differentiated from other materials by the unique risks associated with their release due to accidents. Hristova [1] emphasized the role of transport in the European economy, especially focusing on the transport of DG. Hazardous materials represent an important segment of the transport industry and it is of vital importance for the economy that this transport takes place efficiently and safely through a well-organized logistics chain. Hence, it is essential to meticulously plan transport routes and assess risks to the environment and population, coupled with the training of drivers and personnel involved in the transport of DG, adherence to ADR guidelines, knowledge of regulations, and the implementation of modern systems and software. This study elucidates the concept of risk, the factors influencing the safe transport of DG, the methods for risk assessment and management, the contemporary vehicle tracking systems, and other pertinent entities. A particular focus is given to a case study illustrating the integration of ALOHA and GIS systems to evaluate the dispersion of substances in the event of an accident. This scenario was simulated and visualized near a market in the Stari Aerodrom neighborhood.

Nowadays safety of DG transport is one of the most interesting transportation planning topic. It involves road safety, goods storage, prevention and security [2]. During the transportation of DG, various transportation risks may arise, which complicate transportation planning, as there is no consensus among researchers on a universal model for modeling the transportation risk. Erkut and Verter [3] provided an overview of the models most commonly used for modeling the transportation risk of DG, as well as the importance of quantifying the risk. The quantitative approach to environmental risk assessment has a very important role in supporting decision-makers in risk management, which consists of six steps: selection of the transport mode, the type of facility, and criteria, implementation of safety pillars, evaluation of measurable indicators, and selection and implementation of safety measures. Using the knowledge of all relevant disciplines has a very important role for a qualitative approach to environmental risk assessment [4].

Skills and habits play a very important role in the driver's behavior, where skills stand out especially in the ability to avoid a traffic accident. By combining the skills and decisions that the driver makes at each level, it can directly affect the occurrence of human error and increase the risk level of a traffic accident [5]. In Nigeria, Ambituuni et al. [6] analyzed 2,318 accidents involving tankers transporting DG using a customized risk assessment framework between 2007 and 2012. Analysis of the data collected revealed that 79% of these accidents were caused by human factors, with an emphasis on dangerous driving. Over 70% of the accidents were caused by loss of insulation, which led to spills, fires and explosions. Yang et al. [7] analyzed 322 traffic accidents that occurred during the DG transportation on roads in China from 2000 to 2008. The results showed an increase in the frequency of accidents during the period from 2000 to 2007, with a slight decrease in 2008. In addition, it was found that 63% of traffic accidents occurred in the eastern coastal areas, 25.5% in the central area, while only 10.9% occurred in the western area. Forigua and Lyons [8] found that more than 162 million tons of goods and 21 million tons of DG were transported by road in 2012 in Colombia, with DG in the forms of flammable liquids accounting for 87% and gases for 9%. However, no specific information on the number of traffic accidents with vehicles carrying DG was obtained. The transport of DG in urban areas in Colombia represents a greater risk, because there are not exclusive lanes or routes for this type of transport, i.e. the vehicles can pass through any area or any urban road. In 2014, 87.5% of DG were transported by road in Poland, while 12.5% was transported by rail. Although the transport of DG in Poland is mostly carried out by road, there is no real-time vehicle tracking system [9].

Beczkowska and Grabarek [10] introduced an innovative methodology for risk assessment by considering human errors as a significant factor in the analysis. By using fuzzy logic techniques, values for parameters characterizing the human factor were generated, contributing to better analysis and understanding of the impact of human factors on the probability of accidents during the transport of DG. The study included the probability modeling of accidents, where the risk assessment model took into account various driver characteristics and their impact on driving performance. The main assumption of this work was the linear relationship between driver fatigue and the increase in the number of errors. It was concluded that noise and vibrations play a very important role in the model, as they can cause unpredictable effects in combination with monotony or stress.

Pamučar et al. [11] worked on developing cost and risk assessment models during route planning for the transport of DG in urban areas, using adaptive neuro-fuzzy networks. A specific goal of this study was to test the model through an empirical study in the city of Belgrade, Serbia.

Huang et al. [12] provided necessary information on the risk prevention and quantification and control of the last transport of DG by government decision-makers along the Beijing-Tibet Expressway in China. Technical chlorine was selected as the hazard source in the case study, with the worst-case scenario considered as damage to the container due to a reverse collision in a traffic accident.

Khanmohamadi et al. [13] analyzed spatial vulnerability due to the DG transport with a special focus on railway routes, aiming to identify key areas that are most vulnerable to potential terrorist attacks. ALOHA and ArcGIS software tools were used for vulnerability assessment, including analysis of the affected population and infrastructure in the event of a terrorist attack. The study specifically focused on the transport of chlorine along the Texas-Illinois railroad in the US, developing a route model to identify key points for terrorist attacks.

To ensure safety during the transport of DG, it is essential to manage risk, a complex process involving numerous stakeholders in the hazardous material transportation system. In 1998, the European Environment Agency (EEA) defined the risk management process as decision-making wherein only options that facilitate necessary success are selected from a range of alternatives [14]. After analyzing and assessing the risk, the next step is to reduce the risk by applying various methods and means of prevention and limit the damage caused by the DG transport. The most common way to reduce the risk is to change the route and/or time of transporting DG [15]. One of the biggest problems is the fact that the transport of DG usually takes place during rush hour through the centers of big cities, which significantly increases the risk of danger [16].

Charlier [17] examined the problems associated with the transport, handling and storage of DG in ports. The primary objective was to expand the previous focus on the direct hazard and environmental consequences. The secondary effects of all activities during the transport, handling and storage of DG, as well as the potential legal frameworks that could be applied in such situations were also investigated and analyzed. Das et al. [18] designed a framework for assessing the risk associated with the transport of flammable and volatile waste. The study was conducted in the Calcutta area, where the impact of an unstable vapor cloud explosion on the population was analyzed. The research aimed to develop a procedure for calculating the risk to the population associated with the transport of hazardous waste by using a pharmaceutical production unit as a case study.

2 Methodology

ALOHA is a computer program devised to analyze and model three primary hazards resulting from the chemical release of certain DG, which may cause fire, explosion, or dispersion of toxic gas. The program is intended for individuals who plan the transport of DG and respond in emergency situations caused by the release of these substances into the environment. Developed by the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA) [19], the program's advantage lies in its rapid data processing, which is beneficial for managerial responses in emergency scenarios, thereby minimizing the risk. Utilizing the ALOHA software enables the assessment of the following risks to human health, which may be compromised due to DG release:

• Inhalation of toxic chemical vapor;
• Thermal radiation resulting from fire;
• The effect of wave pressure (caused by the explosion of steam clouds) [19].

In conjunction with GIS software, ALOHA facilitates the visualization of danger zones resulting from the dispersion of toxic gases, fires, and explosions. These danger zones denote areas where exposure surpasses user-defined levels of concern. Following the release of a substance, all points within the danger zone experience a transient exposure that exceeds the defined Level of Concern (LOC). ALOHA's limitation lies in its restriction to airborne chemicals. Conversely, ALOHA offers various models for estimating the rate of matter release from a confined space. By integrating the source strength model and the dispersion model, ALOHA enables the estimation of the spatial extent of toxicity, flammability, and explosion potential of vapor clouds. For the ALOHA software to provide a risk assessment, the user must input the following information:

• City and country name;
• Accident site coordinates;
• Date and time of occurrence;
• Selection of chemical;
• Prevailing weather conditions;
• Tank dimensions, volumes, and chemical exit method;
• Type of building and its urban location status;
• Presence of protective vegetation (e.g., bushes and trees);
• Determination of the LOC.

ALOHA employs various models to estimate the release rate of a chemical from a confined space into the atmosphere as follows:

• Direct model: This model is characterized by the immediate or continuous release of a chemical from a specific point, facilitating increased dispersion;

• Puddle model: This model describes a puddle of a defined size containing a liquid that may either boil or remain non-boiling;

• Tank: This can be cylindrical or spherical, featuring a leaky opening or valve. This container may hold liquid, gas under pressure, or gas in a liquid state under pressure. The chemical may be released from the reservoir directly into the atmosphere or may form an expanding vapor pool;

• Gas pipeline: This pressurized pipe contains gas, which may or may not be connected to the storage tank [18].

The release of various DG, their dispersion, safety measures, consequences, and risk assessment were discussed in this study. The research area is the capital city of Podgorica, specifically the Stari Aerodrom District (Figure 1), which is a strategic location for studying and simulating the release of DG from transport vehicles. Sophisticated ALOHA software was utilized for a detailed analysis of potential scenarios involving the release of dangerous substances. The objective of the scenario is to gain a clear understanding of the potential risks, with an emphasis on improving safety during the transportation of DG and enhancing emergency response in urban areas.

The fundamental data utilized for each scenario individually are:

• The altitude of Podgorica City is 45 meters (148 feet).

• The geographic latitude and longitude for Stari Aerodrom are 42° 25.7’ and 19° 16.3’, respectively;
• The local standard time in Podgorica differs from the Greenwich Mean Time (GMT), which is -1:00;
• The gas exchange rate for a one-story building is 0.60 per hour;
• Protected building (shrubs and trees);
• The coordinates of the accident are 42°25’42.55”N and 19°16’15.95”E.

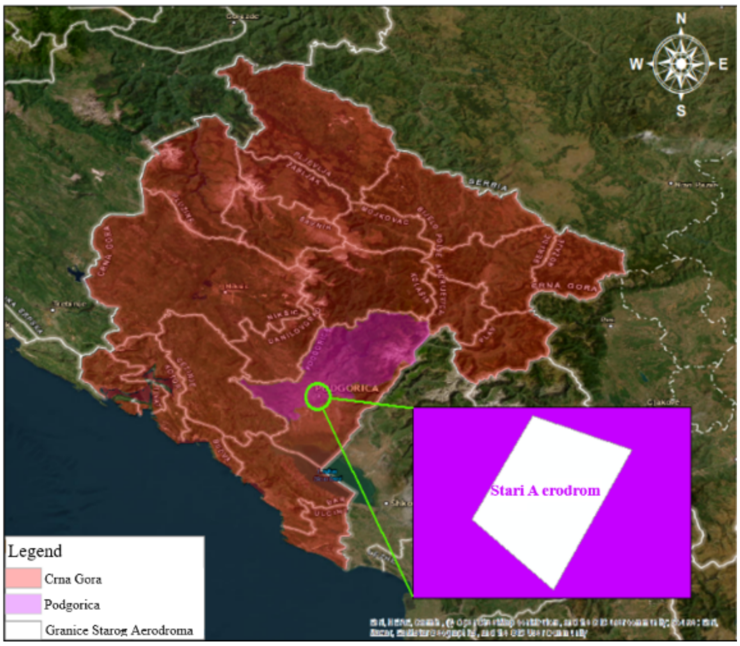

Figure 1. Research area

3 Results

The results of the research obtained using the ALOCHA software for three distinct DG—benzene, chlorine, and methane—pertaining to the previously specified area in the Podgorica City are presented below.

3.1 Case Study 1 (Benzene)

Benzene is a colorless, flammable liquid characterized by a petroleum-like odor. It is less dense than water, exhibits poor solubility in water, and possesses a flash point below 0°F [20]. Benzene vapors are denser than air and can travel considerable distances to an ignition source. This substance is flammable under a wide range of ambient temperature conditions. Exposure to benzene can result in pallor, dizziness, redness, shortness of breath, headache, chest tightness, nausea, vomiting, and coma, among other symptoms.

In the event of a benzene spill, adherence to the following guidelines [20] is necessary:

• In the event of a minor spill, isolate individuals in the affected area to at least 50 meters in all directions;

• In the event of a large spill, initiate an evacuation of no less than 300 meters in the area most affected by the hazardous material, considering wind direction;

• In case of fire, isolate and evacuate all individuals within an 800-meter radius in all directions. Extinguish the fire from a maximum distance or utilize drones;

• If the tank exhibits a color change due to the fire, immediate withdrawal is necessary;
• Eliminate all sources of ignition in the immediate vicinity;
• Avoid contact with the spilled material in the designated area;
• Prevent the entry of substances into waterways, sewers, enclosed spaces, etc.
• Absorb or cover the material with dry soil or sand, and subsequently transfer it to a container;
• Do not use tools that produce sparks to collect the material;
• Utilize eye and skin protection;
• Upon contamination, immediately cleanse the skin;
• If clothing is wet, remove it immediately to mitigate flammability risk;
• An eye wash station must be available, or eyes should be rinsed with water;
• Immediately contact emergency medical services.

Fundamental information about benzene is as follows [20]:

• Class 3;
• UN number: 1114;
• CAS number: 71-43-2;
• AEGL-1 (60 min): 52 ppm;
• AEGL-2 (60 min): 800 ppm;
• AEGL-3 (60 min): 4,000 ppm;
• Molecular weight: 78.11 g/mol;
• Ambient boiling point: 79.9°C;
• Freezing point: 5.5°C.

The two steps required for ALOHA to assess the risk are:

(a) Data on atmospheric characteristics

• Wind speed: 2.24 m/s (breeze);
• Wind direction: NNE;
• Land roughness: urbanized area;
• Total cloudiness;
• Air temperature: 26°C;
• Stability class: D.

(b) Tank data

• Diameter: 2 m;
• Length: 10.53 m;
• Volume: 33,081 l;
• Stored as a liquid;
• Stored at ambient temperature;
• Mass in tank: 25.4 t;
• Liquid volume: 26,465 l; 80% by volume;
• Boiling Liquid Expanding Vapor Explosion (BLEVE) model;
• Tank pressure due to matter release: 67.9 psia;
• Tank temperature due to matter release: 137.9°C.

The following LOCs were established within the scenario:

• LOC (red danger zone) = 10 kW/m^2;
• LOC (orange danger zone) = 5 kW/m^2;
• LOC (yellow danger zone) = 2 kW/m^2.

After inputting all required data, the ALOHA software tool facilitated the visualization of wind direction, spread of matter in kilometers, and LOCs (red, orange, and yellow threat zones). In this scenario, potential death transpired after 60 seconds.

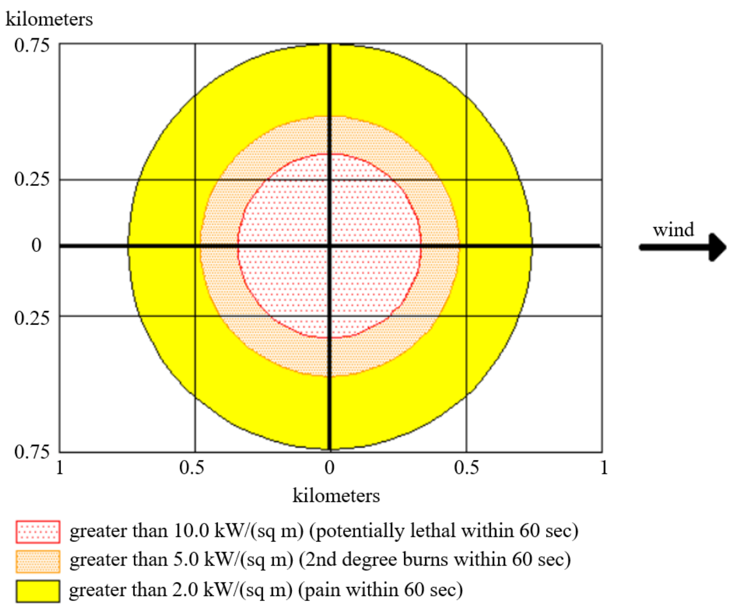

Figure 2. Dangerous zones of benzene

According to the data presented above, the wind speed at the accident location is 2.24 m/s, with a wind direction of 22.5° marked NNE. The maximum thermal radiation downwind at the furthest extent of the red threat zone (0.33 km or 330 m) from the accident center reaches 10 kW/m^2, a level at which fatality ensues within 60 seconds. The maximum thermal radiation within the orange threat zone is 5 kW/m^2 downwind, extending to a maximum distance of 0.48 km (480 m) from the accident center, where second-degree burns occur within 60 seconds. The second zone, denoted as the pain zone, exhibits a maximum thermal radiation of 2 kW/m^2 downwind, extending to a maximum distance of 0.74 km (740 m) from the accident center (Figure 2). The unit kW/m^2 denotes the amount of heat energy transferred to a surface area of 1 m^2 in one second.

After establishing the thermal radiation concentration levels (LOCs), the scenario was integrated and visualized using the ArcGIS software (Figure 3).

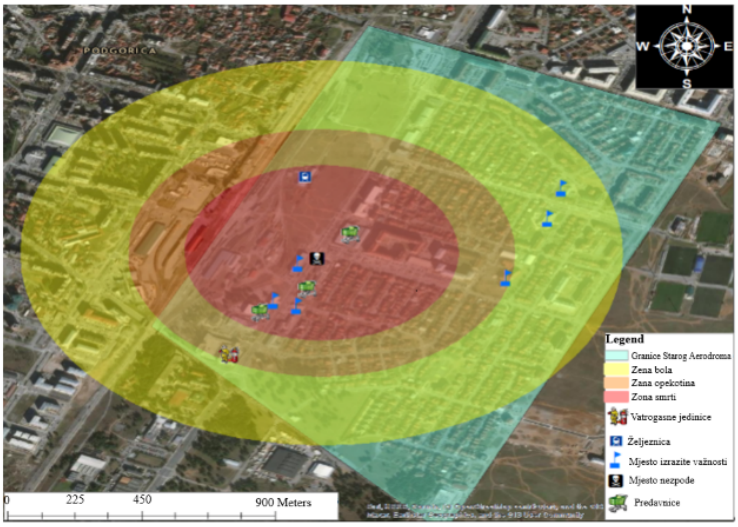

Figure 3. Benzene scenario shown in the ArcGIS software

3.2 Case Study 2 (Chlorine)

Chlorine is a yellow gas characterized by a pungent, suffocating odor and is toxic upon inhalation. This gas is soluble in water and exists as a liquid at room temperature and -35°C. Chlorine possesses oxidizing properties, does not combust directly but promotes combustion, and exhibits explosive reactivity. Prolonged inhalation of low concentrations or short-term exposure to high concentrations adversely impacts human health. Its vapors, being significantly denser than air, tend to accumulate at lower elevations. This substance can incite fires upon contact with flammable materials (e.g., oil and paper) and, when mixed with fossil fuels, can trigger explosions. During chlorine transport within this vicinity, attention should be directed to the distances of the Eco pump (approximately 160 meters) and the INA pump (approximately 230 meters) from the incident site. In the presence of rust, soot, or carbon, chlorine can ignite steel at 100°C and dry steel wool at 50°C. Heating results in the emission of highly toxic fumes, which also occurs when mixed with water or steam. Chlorine is predominantly utilized for water purification, the production of various chemicals, and the bleaching of wood pulp [20].

Should this substance be released from the reservoir, it is imperative to adhere to the following precautionary measures [20]:

- Isolate individuals in the spill or leakage zone by at least 100 meters in all directions;
- If a tanker vehicle is involved in the fire, isolate individuals and consider an initial evacuation within an 800-meter radius in all directions;
- Evacuate the area affected by the gas;
- Avoid low-lying areas;
- Wear prescribed protective clothing and breathing apparatus;
- If it is necessary to stop the flow of gas, utilize a water spray to direct the gas;
- Do not touch the material or walk through it;
- Prevent runoff water from coming into contact with the material;
- If feasible, turn the leaking container so that the gas, not the liquid, escapes;
- Prevent the entry of the material into waterways, sewage, basements, or confined spaces;
- Ventilate the area.

Fundamental information about chlorine is as follows [20]:

• Class 2;
• Hazard labels: 2, 5.1, 8;
• UN number: 1017;
• CAS number: 7782-50-5;
• AEGL-1 (60 min): 0.5 ppm;
• AEGL-2 (60 min): 2 ppm;
• AEGL-3 (60 min): 20 ppm;
• Molecular weight: 70.91 g/mol;
• Melting point: -150°C;
• Boiling point: -30.3°C.

The two steps required for ALOHA to assess the risk are:

(a) Data on atmospheric characteristics

• Wind speed: 1.34 m/s (light air);
• Wind direction: SW;
• Land roughness: urbanized area;
• Sunny;
• Air temperature: 26°C;
• Stability class: B.

(b) Tank data

• Diameter: 2 m;
• Length: 10.53 m;
• Volume: 33,081 l;
• Stored as a liquid;
• Stored at -35°C;
• Mass in tank: 45.6 t;
• Liquid volume: 26,492 l;
• 80% by volume;
• The opening where the material leaks is round in shape;
• The size of the opening is 4 cm;
• The height of the opening where the material leaks is 77 cm;
• The height of the opening at which the matter leaks is at 38.5% of the total height;
• Soil type: concrete (including concrete, asphalt, and others);
• Heavy gas model.

The following LOCs were established within the scenario:

• LOC (red danger zone) = 20 ppm;
• LOC (orange danger zone) = 2 ppm;
• LOC (yellow danger zone) = 0.5 ppm.

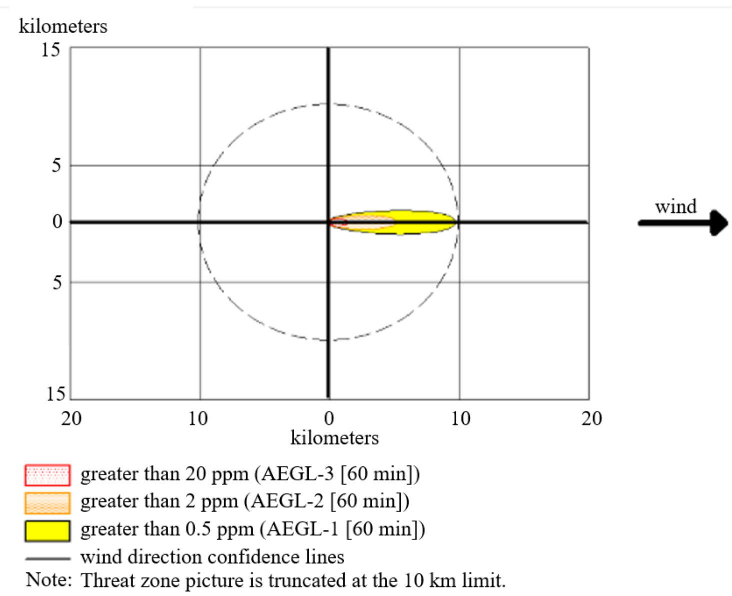

Figure 4. Dangerous zones of chlorine

Based on the data presented, it can be concluded that the wind speed at the location of the accident is 1.34 m/s, while the wind direction is 225° (SW). Figure 4 indicates that the maximum concentration of matter, expressed in ppm, downwind at the maximum distance of the red threat zone (approximately 1.60 km from the center of the accident), is 20 ppm. The maximum concentration of matter in the orange threat zone is 2 ppm downwind, at a maximum distance of approximately 5 km from the center of the accident. The second zone exhibits a concentration of matter of 0.5 ppm downwind, at a maximum distance of approximately 10 km from the center of the accident. The diagram also illustrates that the threat zones emerge over a period of 60 minutes with varying concentrations of matter. The dotted line in the diagram represents the wind direction.

After delineating the level of thermal radiation concentrations (LOCs), the projected scenario was integrated and visualized within the ArcGIS program (Figure 5).

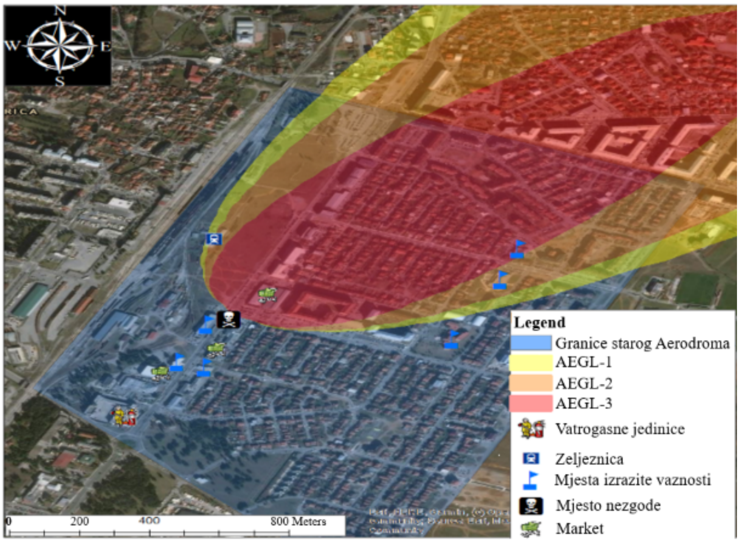

Figure 5. Chlorine scenario shown in the ArcGIS software

3.3 Case Study 3 (Methane)

Methane is a colorless, odorless gas that readily burns and evaporates either rapidly or completely at atmospheric pressure. Its vapors are lighter than air, and containers may rupture violently upon prolonged exposure to fire. This substance acts as a reducing agent and can induce explosions when combined with strong oxidants such as bromine pentafluoride, chlorine, iodine, or liquid oxygen. The mixture of liquid oxygen and methane forms an explosive combination. Furthermore, contact between cooled liquid methane and water results in vigorous boiling and rapid evaporation due to significant temperature differences. If the water is hot, the liquid methane can overheat and detonate. High concentrations of methane pose a suffocation hazard. Methane is employed in the production of various chemicals and as a component of fossil fuels. In this scenario, a model was applied where the material leaks from a tank and burns, known as jet fire. The release of the material from the tank results in the formation of a puddle which subsequently ignites [20].

In the event that this substance is released from the reservoir, adherence to the following precautionary measures is required [20]:

- Isolate the spill area within a 100-meter radius in all directions;
- Consider an initial evacuation of at least 800 meters in all directions;
- In the event of a fire on a tanker vehicle, isolate individuals at a minimum distance of 1,600 meters in all directions;
- A mixture of hydrogen and methane (UN 2034) can combust with an invisible flame; thus, the use of a thermal camera for flame detection is recommended;
- Extinguish the fire from the maximum possible distance or utilize drones;
- Cool the containers with chilled water until the fire is extinguished;
- When using water to extinguish the fire, avoid spraying water on safety devices to prevent freezing;
- Maintain a safe distance from the fire-affected tank;
- Eliminate all ignition sources;
- Refrain from touching the material and avoid walking through it;
- Use water spray to minimize evaporation;
- Ensure that runoff water does not come into contact with the material;

• Prevent the spread of vapor through sewers, ventilation systems, and enclosed spaces.
Fundamental information about methane is as follows [20]:
• Class 2;
• UN number: 1971;
• CAS number: 74-82-8;
• AEGL-1 (60 min): 65.000 ppm;
• AEGL-2 (60 min): 230.000 ppm;
• AEGL-3 (60 min): 400.000 ppm;
• Molecular Weight: 16.04 g/mol;
• Melting point: -296.5°C;
• Boiling point: -306°C.
The two steps required for ALOHA to assess the risk are:
(a) Data on atmospheric characteristics
• Wind speed: 5 m/s (moderate);
• Wind direction: NE;
• Land roughness: urbanized area;
• Sunny;
• Air temperature: 25°C;
• Stability class: D.
(b) Tank data
• Diameter: 2 m;
• Length: 10.53 m;
• Volume: 33,081 l;
• Stored as a liquid;
• Stored at -161°C;
• Mass in tank: 12.3 t;
• Liquid volume: 26,465 l;
• 80% by volume;
• The opening where the material leaks is round in shape;
• The size of the opening is 4 cm;
• The height of the opening where the material leaks is 77 cm;
• The height of the opening at which the matter leaks is at 38.5% of the total height;
• Soil type: concrete (including concrete, asphalt, and others);
• Jet fire model.
The following LOCs were established within the scenario:
• LOC (red danger zone) = 10 kW/m^2;
• LOC (orange danger zone) = 5 kW/m^2;
• LOC (yellow danger zone) = 2 kW/m^2.

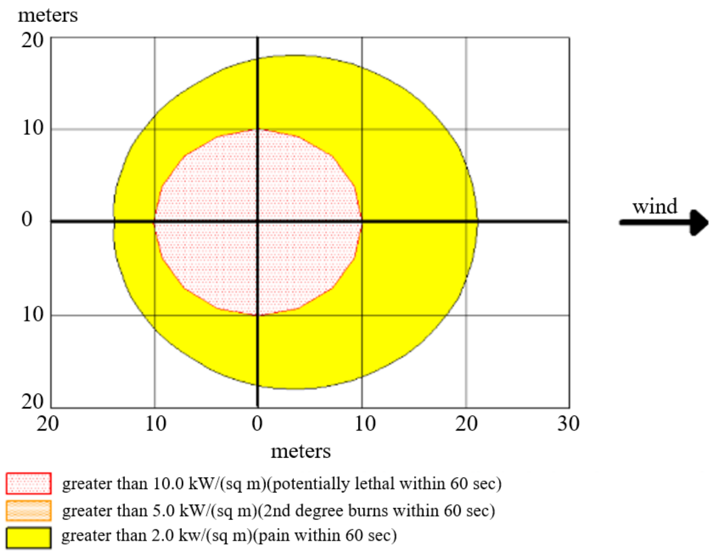

Figure 6. Dangerous zones of methane

Upon inputting the required data, ALOHA presented wind direction, spread of matter measured in kilometers, and LOCs (red and yellow threat zones). In this context, potential death occurred after 60 minutes.

Based on the data presented, it can be concluded that the wind speed at the accident site is 5 m/s, with a wind direction of 45° NE. According to Figure 6, the maximum thermal radiation, expressed in kW/m^2, downwind at the maximum distance of the red threat zone, approximately 9.87 m from the accident center, is 10 kW/m^2. The second zone exhibits a matter concentration in the environment of 2 kW/m^2 downwind, at a maximum distance of approximately 21 m from the accident center. Additionally, threats occur within a 60-second period, with varying thermal radii in the environment.

After establishing the levels of thermal radiation concentrations (LOCs), the designed scenario was integrated and visualized in the ArcGIS program (Figure 7).

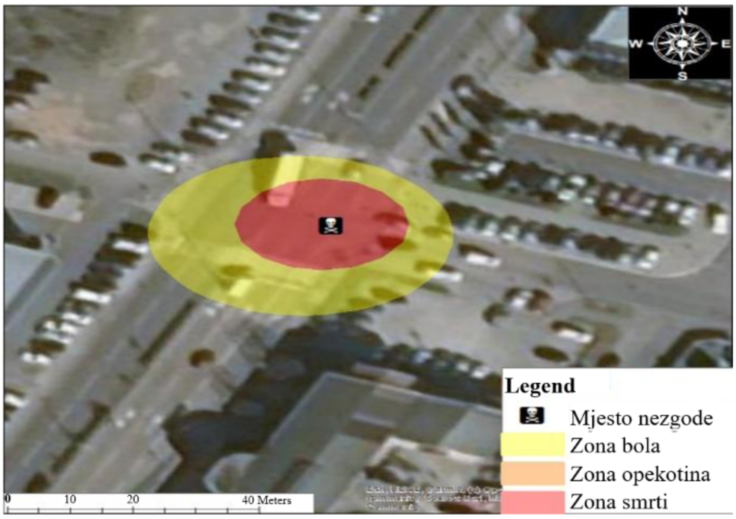

Figure 7. Methane scenario shown in the ArcGIS software

4 Discussion

This study examined three potential scenarios utilizing the reservoir model. For benzene, chlorine, and methane resulting from the accident, three release mechanisms of hazardous substances were identified. Specifically, the BLEVE effect was chosen for benzene; the dispersion of substances without ignition was selected for chlorine; and the jet fire effect was chosen for methane. It can be posited that the chlorine scenario has extensive impacts on the environment, population, and property. In this scenario, the maximum zone of influence (AEGL-1 or yellow zone) extends 10 km, within which the substance concentration in the environment is 0.5 ppm. The deadliest zone (AEGL-3), termed the red zone, reaches approximately 5 km downwind from the accident site, with a maximum substance concentration of 20 ppm. Additionally, it is crucial to note that in this scenario, the threat zone is defined as occurring within a 60-minute period. Contact with this substance within this timeframe can be fatal if inhaled and may cause burns, bronchitis, or chronic lung conditions. The benzene scenario is considered the worst-case scenario, where the explosion of boiling liquid (BLEVE) results in potential fatality within 60 seconds. Notably, within the red zone, also referred to as the death zone, the maximum thermal radiation of 10 kW/m^2 affects an area up to 330 meters from the accident's center. This zone encompasses markets with high consumer traffic, the Mediterranean University, the Eko gas station, and other critically important facilities. The scenario is considered particularly severe due to the potential BLEVE effect, which could result in catastrophic consequences. The impact on the gas station could trigger an explosion with disastrous ramifications. The influence of the orange zone extends up to 480 meters from the center of the accident, with a maximum thermal radiation of 5 kW/m^2, while the yellow zone (AEGL-2) affects an area up to 740 meters from the center, with a maximum thermal radiation of 2 kW/m^2. It is important to note that within the orange and yellow zones are the elementary school Pavle Rovinski, the kindergarten Dragan Radulović, the health center at Stari Aerodrom, and other significant facilities.

5 Conclusions

The transport of DG is a complex process that carries various risks for the population, infrastructure, and the environment. Therefore, if the safety guidelines prescribed by ADR are not followed during loading, transport, unloading, and storage, there may be catastrophic consequences for the environment, people, and property. During the transport of DG, it is inevitable to pass through urban areas, which increases the need to apply effective methods of transport risk assessment and management.

The integrated application of contemporary real-time vehicle tracking systems and the ALOHA software constitutes a critical strategy for the swift identification of problems and risks, as well as analysis and response during emergency situations. These technological solutions facilitate adequate planning and risk reduction concerning environmental and human health. For managers overseeing the transport of hazardous materials, it is imperative to expeditiously process data and assess risks to the populace and the environment along the projected route. The ALOHA software, a computational program, enables rapid processing of information, identification of potential risks, and assessment of the impact of DG on human health. The ALOHA software plays an essential role in the analysis and modeling of hazards arising from chemical releases of hazardous substances, which, in combination with the GIS software, allows users to visually display danger zones.

The study examined three potential scenarios, selecting the reservoir model for analysis. For benzene, chlorine, and methane released as a consequence of the accident, three distinct release mechanisms of DG were identified. Specifically, the BLEVE effect was selected for benzene, the dispersion or spread of hazardous substances without ignition for chlorine, and the jet fire effect for methane. It can be asserted that the chlorine scenario exerts broad impacts on the environment, population, and property. Conversely, the benzene scenario is deemed the most severe, where the explosion of boiling liquid (BLEVE) potentially results in death within 60 seconds. Notably, in the red zone or death zone, the maximum thermal radiation of 10 kW/m^2 affects an area extending up to 330 meters from the accident's center, encompassing a market that attracts a substantial number of consumers. This scenario is particularly perilous due to the BLEVE effect's potential to cause catastrophic consequences, especially impacting the gas station within the risk zone, thereby amplifying the explosion and precipitating a disaster.

Finally, in Montenegro, it is imperative to promote the utilization of the ALOHA and GIS software tools for swift risk assessment, evaluating the impact of DG on the environment, property, and population, as well as selecting the route with the least risk. Additionally, statistical analyses of traffic accidents involving vehicles transporting DG should be established.

Funding

This paper has been supported by Erasmus+ Capacity Building in Higher Education projects, 101082187-DGTRANS-ERASMUS-EDU-2022-CBHE, "Transport of DG-Modernization of Curricula and Development of Trainings for Professionals in the Western Balkans HEIs (DGTRANS)."

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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