HAZARDS OF THE ROAD TRANSPORTATION OF HAZARDOUS MATERIALS

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Abstract: A lot of substances and items are transported by road, sea, rail and air every day. The biggest hazard is created by the transportation of hazardous substances with flammable, caustic or toxic properties. The hazard level increases if such substances are transported through densely populated areas. Traffic intensity, the technical condition of vehicles, drivers’ errors or ignorance and non-compliance with legal regulations are examples of factors that can lead to potential failures in the transport sector. Accidents can cause an uncontrolled release of dangerous gases or liquids, resulting e.g. in environmental degradation or a hazard to humans. The article presents the issues related to the hazards presented by road transportation of hazardous materials. Examples are shown of potential effects of accidents and hazard zones arising due to a release of selected hazardous substances, such as chlorine, ammonia, petrol, diesel oil or LPG.
Keywords: hazardous materials, hazards, road transportation

1. INTRODUCTION
A lot of substances and items are transported by road, sea, rail and air every day. Safe, fast and economic carriage of goods is the basis for the development of trade both on the international and domestic scale. It also contributes to the economic development of countries (Eurostat, 2019; Gerbec, 2008; GUS, 2019; Klimecka-Tatar, 2015). Inland transport of goods in the European Union in the years 2012-2017 rose by 11.1%. Over the years, road transportation has remained the primary way of transport within the European Union (cf. Fig. 1). The member state with the highest share of road transportation is Germany (27.5% of the total number of tonne-kilometres in the international road transport). France comes second with 17.8%. Poland, with the share of 8.7%, is in the third place (Eurostat, 2019).
The continuous increase in the carriage of goods involves a rise in the share of transport of hazardous substances. According to the Eurostat database, the transport of dangerous goods in the EU rose year by year from 73 billion tonne-kilometres in 2013 to more than 83 billion tonne-kilometres in 2017. In the EU member states, the highest increase in the transport of dangerous goods can be observed in Slovakia (117.5%), Sweden (86.4%) and Slovenia and Greece (61.2% each). Ireland, Luxembourg, Denmark and the United Kingdom, on the other hand, saw the biggest drop in the transport of dangerous goods (-69.3%, -28.1%, -18.3% and 13.9%, respectively) (Eurostat, 2019).

Dangerous goods can involve flammable, toxic and/or caustic substances. If they are released in road transport, due to an accident for example, they can pose a substantial hazard to humans, property and the environment. The hazard level is additionally increased if such substances are carried through populated areas. Therefore, the transport of dangerous goods presents a considerable challenge to freight organizers, and the safety of transportation affects a number of industries where hazardous substances are utilized as a raw material or an auxiliary feedstock in many chemical and technological processes (Rogalski and Pyza, 2018; Yilmaz et al., 2016).

The paper presents the basic issues related to road transportation of hazardous materials. Analyses are conducted of example potential scenarios of dangerous events, such as a fire or explosion following accidents involving such substances. The ranges are determined of potential hazard zones arising due to the impact of negative effects.
of a sudden release of selected hazardous substances, such as ammonia, chlorine, LPG, petrol and diesel oil.

2. IDENTIFICATION OF HAZARDOUS MATERIALS

Hazardous materials are defined as substances or objects that can create sudden and uncontrolled hazards to humans or the environment due to their physicochemical properties. These are substances that are allowed for carriage only in compliance with the conditions stipulated in the European agreement concerning the international road transport of dangerous goods (the ADR treaty). The agreement was signed in Geneva on 30 September 1957 and it is updated every two years. Poland joined the agreement in 1975 and since then it has followed the treaty guidelines, making necessary adjustments in its own regulations in the area. In Poland, the transport of dangerous goods is regulated, among others, by the Act of 19 August 2011 on the carriage of dangerous goods or the Regulation of the Minister of Transport, Construction and Marine Economy of 25 April 2012 concerning the report on the checks of the road transport of dangerous goods. Other guidelines in this matter are also included in the Regulation of the Minister of Infrastructure and Development of 7 May 2015 on obtaining a certificate of an advisor for the safety of the transport of dangerous goods (Dangerous Goods Safety Advisor).

Under the ADR treaty, dangerous goods are divided into 13 classes, depending on the kind of hazard they create. Each such material is uniquely marked using a four-digit number following the letters UN and included in one of three packaging groups. It is also named and classed according to the ADR. These four items of information suffice for correct identification of each hazardous material (Dyrektywa ADR, Pająk et al., 2016; Pusty, 2007; Rogalski and Pyza, 2016).

Table 1
ADR classes of dangerous goods

| Class 1 | Explosive substances and articles |
|---------|----------------------------------|
| Class 2 | Gases, further divided into flammable, non-flammable and poisonous gases |
| Class 3 | Flammable liquids |
| Class 4.1 | Flammable solids, self-reactive substances and solid desensitized explosives |
| Class 4.2 | Substances liable to spontaneous combustion |
| Class 4.3 | Substances which, in contact with water, emit flammable gases |
| Class 5.1 | Oxidizing substances |
| Class 5.2 | Organic peroxides |
| Class 6.1 | Toxic substances |
| Class 6.2 | Infectious substances |
| Class 7 | Radioactive material |
| Class 8 | Corrosive substances |
| Class 9 | Miscellaneous dangerous substances and articles |

Source: (own study based on Dyrektywa ADR; Yilmaz et al., 2016)

The ADR agreement consists of the main part and two integral annexes: Annex A and Annex B. Apart from the classification of dangerous goods (cf. Table 1), the agreement sets out the regulations concerning appropriate packaging and transport of individual materials. It also provides the guidelines for the marking of the goods, the
packaging and the vehicles carrying them. The obligations of the transport chain participants are also defined, together with the principles of performing consignment procedures. All this information is included in Annex A to the agreement. Annex B stipulates the conditions for the transport of individual dangerous materials, the technical conditions that must be satisfied by the transporting vehicles, the conditions for the loading and unloading of individual materials and the regulations concerning the transport necessary documentation (Dyrektywa ADR; Pająk et al., 2016; Pusty, 2007; Rogalski and Pyza, 2016).

3. ROAD TRANSPORT OF DANGEROUS GOODS

Three methods of carriage can be distinguished in the process of the road transport realization. The first consists of vehicles transporting dangerous materials in pieces of consignment, i.e. in items of packaging intended for carriage, such as cylinders, boxes, etc. The second comprises vehicles transporting dangerous materials in bulk, with no packaging, and the third – tankers. The means of transport should be adequately equipped and marked in compliance with the requirements set out in the ADR. Relevant marking is to be appropriately placed on consignment items, plates, tankers, containers and vehicles in the form of labels/stickers, plates and notices. The class of transported dangerous materials is identified using a system of markings, two examples of which are presented in Fig. 3. The marking items should be made of a material resistant to variable atmospheric conditions. They should also ensure good visibility of the colours and symbols. Vehicles transporting dangerous materials should additionally be equipped with a 30x40 cm orange plate with the marking of the material and the hazard. The plates should be put on the transporting unit front and back, perpendicularly to the vehicle longitudinal axis (cf. Fig. 4) (Dyrektywa ADR; Kopaczewski and Nowacki 2019; Pająk et al. 2016; Pusty, 2007; Rogalski and Pyza, 2016).

Fig. 3. Hazard label (Class 1, Subclass 1.5)
Fig. 4. Plate with hazard numbers

Source: (own study based on Dyrektywa ADR)

Another important factor in the road transport of dangerous goods are the obligations imposed on the process participants. The obligations should be fulfilled solidly, or else no transport procedure must be started. Relevant regulations ensure control at every stage of the process, and the tasks to be performed by consignors, carriers and consignees of hazardous materials are clearly defined. The sender prepares dangerous goods for transport and his fundamental duty is to make sure that they are classed correctly. He is also obliged to provide the carrier with relevant documents (permits, certificates, etc.) and to ensure appropriate marking of the consignment. The carrier's duty, among others, is to check the completeness of documentation and the technical control of vehicles. The carrier is also obliged to make sure the transporting unit is adequately equipped. The recipient of dangerous goods must not delay the unloading and on its completion, if required by relevant regulations, he is obliged, among others, to clean and disinfect the vehicles.
Properly conducted transport of dangerous goods improves the process safety and ensures protection of other road users. An important factor that diminishes the risk related to transportation of hazardous materials is appropriate training of all the transport chain participants, e.g. forwarders, warehouse workers, etc. Each driver should also complete a relevant training course because he is the person responsible for the hazardous material in transit. Acting responsibly, he can minimize the risk of undesirable events (Dyrektywa ADR; Kopaczewski and Nowacki, 2019; Pająk et al. 2016; Pusty, 2017; Rogalski and Pyza, 2016).

4. HAZARDS RELATED TO TRANSPORTATION OF DANGEROUS MATERIALS
In Poland, the transport of dangerous materials in 2018 totalled about 9 billion tonne-kilometres. The responsibility for the safety of road transportation of dangerous materials lies with all participants in the chain. Accidents that occur during the road transport of dangerous goods may create a considerable hazard to human life and health. They can damage the infrastructure and result in environmental pollution and contamination. Despite strict legal regulations aiming to minimize and eliminate the hazards, road accidents and catastrophes cannot be avoided completely (Kopaczewski and Nowacki, 2019, Pająk et al. 2016). One of the most tragic events of this type was the catastrophe that took place in Spain in 1978. A road tanker containing 23 tons of propylene became unsealed and 217 people were killed and another 200 were injured. One of the most tragic accidents this year took place in Tanzania: a road tanker became unsealed and oil was spilled. The people on the road tried to steal the leaking fuel. There was an explosion and 75 people died.
Among the causes of accidents in the road transport of dangerous materials, man is the most essential link. Ill-considered actions or omissions, and sometimes unawareness of the effects of potential hazards on the part of the transport chain participants, are only some sources of accidents (Pająk et al., 2016).
Other factors that create hazards related to the road transport of dangerous goods include the great number of performed transports, types of packaging and of the marking of transport units which do not comply with the ADR guidelines, inappropriate technical condition of packaging and containers used in transit, poor condition of roads, lack of specifically determined safe transport routes, inappropriate loading, speeding, driving at speeds which are unreasonable in given weather conditions, wrong manoeuvres, disrespect for the principles of transportation of hazardous materials or traffic regulations, no or incorrectly filled consignment notes, high risk of road collisions, lack of proper training and improper organization of the transport of hazardous cargoes. The high unpredictability of the failure site also affects the hazard level significantly (Kopaczewski and Nowacki, 2019; Pająk et al. 2016; Pusty, 2007; Rogalski and Pyza, 2016).

5. ANALYSIS OF EFFECTS OF EXAMPLE FAILURES IN TRANSPORTATION OF HAZARDOUS MATERIALS
Hazardous materials can be liquid, gaseous or solid. They can be carried using tankers, containers, cylinders, etc. In Poland, they are most often transported using road tankers. The road transport is dominated by liquid fuels, which constitute over half of dangerous goods. Liquefied gases (e.g. propane-butane, chlorine, ammonia), acids and hydroxides are the second biggest group. The pie chart in Fig. 5 illustrates the
share of individual types of the carried substance in the road transport of dangerous goods in the European Union (Eurostat, 2019; GUS, 2019).

Fig. 5. Road transport of dangerous goods by type in 2017, the European Union (% share in tonne-kilometres)

Analysing road accidents involving hazardous materials in the years 2010-2015, the biggest numbers occurred in the transport of diesel oil (26%), LPG (13%) and petrol (5.2%). Obviously, this results from the fact that these hazardous substances are transported by road the most often. Next come, among others, liquefied nitrogen, nitric acid, acetylene, environmentally unfriendly material – liquid and n.o.s., paints, xylenes, propane, ethanol, etc. (Eurostat, 2019; GUS, 2019; Pająk et al. 2016).

As already mentioned, the road transport of hazardous materials presents an essential problem. One consequence of a road accident involving a tanker can be an uncontrolled release of a considerable amount of a substance which is flammable, toxic, caustic, etc. The scenario of a dangerous event started by a release of such a substance can lead to dangerous fires, explosions or clouds with a lethal concentration of toxic constituents.

Below are the results of example analyses of the consequences of a release of selected substances that can be transported by road. The analyses are conducted using the PHAST v6.7 software package. The scenarios under consideration concern a catastrophic, violent release of a specific volume of a hazardous substance due to e.g. a road tanker accident.

- **LPG** – UN Number: 1965, Proper Shipping Name: Hydrocarbon gas mixtures, liquefied, n.o.s., Class 2. LPG is a propane-butane mixture. It is one of the most popular ecological and alternative fuels used to drive vehicles. But it is also used in heating appliances, cookers, etc. LPG is also utilized in industrial processes, e.g. to feed technological lines or for works involving the use of gas-fuelled burners. Due to its composition, LPG is a flammable gas. Incorrect transport and use of LPG can lead to an uncontrolled release of the mixture creating a fire or an explosion risk. One of the most tragic LPG road tanker accidents took place in India in 2012. The tanker became unsealed and the release of the gas caused a fire, an explosion and the BLEVE phenomenon (Stolecka, 2018).

The pictures below show example ranges of hazard zones created due to a fire and the BLEVE phenomenon following a release of LPG from a 20,000 litre road tanker. The presented hazard zones are related to the impact of the fire-generated heat flux value causing human death (37.5 kW/m²) and serious injuries to humans (12.5 kW/m²). For the LPG explosion, the zones are related to the following values
of the generated pressure wave: 100kPa (causing 1% of human deaths) and 35 kPa (causing serious damage to buildings and structures, and – in the case of humans – lung damage) (Stolecka, 2018).

![Diagram](image1)

**Fig. 6. Range of hazard zones related to the BLEVE phenomenon and the LPG explosion**

- **Ammonia** – UN Number: 1005, Proper Shipping Name: Ammonia, anhydrous, Class 2. In the temperature of 20°C ammonia is a colourless gas with a pungent odour. It is an inorganic nitrogen-hydrogen compound used first and foremost to produce artificial fertilizers and to make urea and nitric acid, medicines and cosmetics. Ammonia is also used as the cooling agent in refrigerating systems. The compound is extremely toxic. In concentrations of 400-650 ppm, it causes irritation of the throat and eyes. Higher concentrations, i.e. 2500-4200 ppm, are dangerous if exposure is longer than 30 minutes. Concentrations exceeding 4650 ppm are lethal for humans (Grupa Azoty, 2015, Ubowska 2018). One of the most tragic accidents involving a road tanker transporting ammonia took place in the USA in 1976. A semitrailer carrying about 30,000 litres of anhydrous ammonia fell off a motorway ramp. The tanker shell was ruptured and the contents spilled all over the place. A cloud with a lethal concentration killed 7 people and caused injuries to 200 more. The picture below presents the range of an example hazard zone (with a concentration higher than 4650 ppm) arising due to a sudden release of 20 m³ of ammonia.

![Diagram](image2)

**Fig. 7. Hazard zone due to a release of ammonia**

- **Petrol and diesel oil** – UN Number: 1203, Proper Shipping Name: Gasoline or petrol or motor spirit, Class 3, and UN Number: 1202, Proper Shipping Name: Gas oil or diesel fuel or heating oil, Class 3. These are the most popular conventional fuels
used to drive vehicles. Due to their common occurrence, they have an established position on the fuel market and this makes them the hazardous substances transported by road the most often. Petrol is a liquid mixture of hydrocarbons with a boiling point included in the range of 30-215°C. Its constituents are made of molecules with carbon atoms ranging from C_4 to C_{12}. It is used in vehicles with spark-ignition engines. Diesel oil is a mixture of hydrocarbons with the number of carbon atoms from C_{11} to C_{25} and the boiling point range of 150-400°C. The fuel drives engines with high, medium and low revolution numbers: >1000 rpm, 300-1000 rpm and <300 rpm, respectively. Depending on this parameter, it may differ in chemical composition and operating characteristics.

Petrol and diesel oil are flammable liquids. The hazard created by their release is mainly related to the flammability of the fuel vapours. It should be noted that petrol vapours are easier to ignite. A diesel oil release also presents a hazard but this fuel is less flammable, which is due to its smaller volatility in normal temperatures (PKN Orlen, 2018; PKN Orlen, 2018; Stolecka, 2018; Stolecka 2018).

The Fig. 8 present the ranges of hazard zones arising due to a release and immediate ignition of a pool of petrol and diesel oil assuming that the entire content of the damaged road tanker is spilled. The ranges of the zones are related to the impact of the fire-generated heat flux with the value causing human death, i.e. 37.5 kW/m^2, and with the value causing serious injuries to the human body, i.e. 12.5 kW/m^2.

- **Chlorine** – UN Number: 1017, Proper Shipping Name: Chlorine, Class 2. Chlorine belongs to the family of halogens. It is a gas with a green and yellow colour and an unpleasant smell. Chlorine is commonly used in water treatment plants, swimming pools and water supply systems to ensure appropriate bacteriological quality of water. It also finds application as a disinfectant and a bleaching agent. It plays an important part in industry, e.g. in the making of medicines, paints and solvents. Chlorine is considered as one of the ten most hazardous chemical substances, a release of which may cause serious harm to the human body and death. It leads to irritation of the respiratory system, skin and eyes. Chlorine concentration of 1 ppm causes slight irritation of eyes and dryness in the throat. Concentrations at the level of 40-60 ppm cause lung damage for exposure exceeding 30 minutes. If the concentration level is higher than 1000 ppm, death occurs. One of the most tragic accidents related to the road transport of chlorine took place in China in 2005. A road tanker became unsealed and 27 people died and another 285 suffered poisoning. About 10,000 people had to be evacuated due to the emergency (Avantor Performance Materials, 2018).
The Fig. 9 presents the range of a hazard zone (with a concentration higher than 1000 ppm) arising due to an immediate release of 20 m$^3$ of chlorine.

4. CONCLUSIONS

Every day huge amounts of dangerous goods are transported by road in Poland and in the entire European Union. The potential hazard arising from possible accidents of vehicles carrying these substances should not be underestimated. The accidents can be a source of serious fires, explosions or pollution and contamination affecting humans, the infrastructure and the natural environment. Control and enforcement of appropriate requirements and regulations governing the transport of dangerous goods should not only raise the road users' awareness of potential hazards but also substantially reduce the number of failures resulting from random events and those caused by human fault.

The hazard level and the kind of potential consequences of a failure will vary depending on the substance. They will result from different states of aggregation, different properties, different transport parameters or different accident scenarios. This is confirmed by the results of the analyses presented in the paper. The hazard zone related to the ignition of a flammable mixture (LPG) and causing human death will reach the range of about 80 metres from the failure site. The same hazard zone in the case of a failure and fire of a road tanker carrying a flammable liquid (petrol or diesel oil) will reach the range of about 20 metres. The example analysis of an accident involving a toxic substance (ammonia) indicates that the hazard zone causing human death can cover the area of about 75 m$^2$.

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