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METHODS FOR CATEGORIZING ROAD TUNNELS ACCORDING TO DANGEROUS GOODS REGULATIONS

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RESEARCH ARTICLE

ABSTRACT: According to the ADR Agreement, road tunnels should be assigned a specific tunnel category regarding the passage of dangerous goods. The categorization shall be based on examining the dangers of explosion, release of toxic gas or volatile toxic liquid and fires, which may cause numerous victims or serious damage to the tunnel structure. EU Tunnel Directive 2004/54/EC aims to ensure a minimum level of safety for users in road tunnels in the Trans-European Road Network. EU member states are required to develop, at national level, their own detailed methodology for tunnel risk assessment. Different risk models exist in the literature, however in many European countries the QRAM (Quantitative Risk Assessment Model) is the one most widely used and can satisfy the regulatory framework for tunnel categorization. In this paper, a methodological approach has been presented using the QRAM for determining optimum tunnel categorization according to ADR Agreement requirements.

KEY WORDS: *road tunnels, dangerous goods - ADR, tunnel category, risk assessment*

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METODE KATEGORIZACIJE DRUMSKIH TUNELA PREMA PROPISIMA O PREVOZU OPASNIH MATERIJA

REZIME: Prema ADR sporazumu, drumskim tunelima treba dodeliti posebnu kategoriju tunela u pogledu prolaska opasnih materija. Kategorizacija će se zasnivati na ispitivanju opasnosti od eksplozije, ispuštanja toksičnog gasa ili isparljive otrovne tečnosti i požara, koji mogu izazvati brojne žrtve ili ozbiljna oštećenja konstrukcije tunela. Direktiva EU o tunelima 2004/54/EC ima za cilj da obezbedi minimalni nivo bezbednosti za korisnike u putnim tunelima u transevropskoj putnoj mreži. Od država članica EU se zahteva da razviju, na nacionalnom nivou, sopstvenu detaljnu metodologiju za procenu rizika od tunela. U literaturi postoje različiti modeli rizika, međutim u mnogim evropskim zemljama KRAM (model kvantitativne procene rizika) je onaj koji se najviše koristi i može da zadovolji regulatorni okvir za kategorizaciju tunela. U ovom radu je predstavljen metodološki pristup korišćenjem KRAM za određivanje optimalne kategorizacije tunela prema zahtevima ADR sporazuma.

KLJUČNE REČI: *drumski tuneli, opasni teret - ADR, kategorija tunela, procena rizika*

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INTRODUCTION

Tunnels have played an essential role in modern transportation systems since the mid-20th century. They reduce distances, represent stable connections free from the influence of seasonal and weather conditions and relieve urban areas from noise, exhaust fumes and dust. While most engineering techniques concerning tunnel construction and safety requirements have been continually improving, the problem of dangerous goods transport through tunnels has not been satisfactorily solved yet, [10].

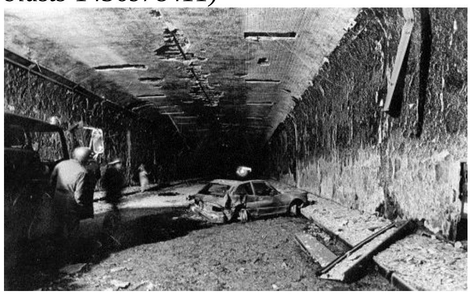
A serious incident involving dangerous goods in a tunnel can be very costly in terms of human lives, the environment, tunnel damage and transport disruption. On the other hand, needlessly banning dangerous goods from tunnels may create unjustified economic costs. There is significant risk of fire and explosion when transporting dangerous goods in a tunnel. Figure 1 shows some severe tunnel fire accidents, [15]:

- On 24 March 1999. a dramatic fire occurred in the Mont Blanc tunnel between France and Italy. It was initiated by a heavy goods vehicle which stopped near the middle of the tunnel and immediately burst into flames. The fire spread over 34 vehicles and was finally extinguished after 53 hours, 38 road users and a fireman lost their lives in the drama and the tunnel was seriously damaged and closed the tunnel for three years, Figure 1a, [15].
- In March 2014, a rear-end collision accident involving two methanol tankers occurred in the Yanhou tunnel in China, causing 40 deaths, 12 injured and 42 vehicles destroyed, [5,14].
- In July 2015 an incident occurred in a steep road tunnel in Norway (Skatestraum tunnel) with an tanker and a trailer carrying 16,500 l petrol which was incidentally released halfway up a 1 km long sloped tunnel (10%) and hit a tunnel wall. The initial fire size was estimated to be 212 MW and the maximum heat release rate including the tank fire was estimated to be 440 MW, Figure 1b. [5,14,15],
- In the Tauern Tunnel in Austria in 1999, one person died and 36 were injured when the temperature inside the tunnel peaked at around 1,000°C, Figure 1c, [5,14,15].
- In Caldecott Tunnel (USA) fire, in April 7, 1982, car struck the wall, blocking the roadway about halfway through the tunnel. A tanker truck hauling gasoline crashed into car and then was struck from behind by a bus, which somehow ended up outside the tunnel. The gasoline tanker inside ignited, creating an inferno that killed seven people, Figure 1d, [5,14,15].

Mont Blanc tunnel, in 1999. (https://www.onlinesafetytrainer.com/the-mont-blanc-tunnel-fire-of-1999/)

Skatestraum tunnel, Norway, in 2015., (https://www.wsj.com/articles/norwegian-authorities-fear-tunnel-collapse-after-blasts-1436978411)

Tauern tunnel, Austria, in 1999, (https://www.researchgate.net/publication/284676361_Fire_proof_geopolymer_cements)



Caldecott Tunnel, USA, in 1982, (https://www.pressdemocrat.com/article/news/a-fiery-tomb-remembering-one-of-the-bay-areas-most-terrifying-disasters/)

Figure 1 Tunnels after fire accidents, [15]

All these events indicated the vulnerability of tunnels as infrastructural facilities and the great risk to people's lives, the economy and the environment. Tunnel fire accidents have shown that the toxic effects of the trapped smoke from the fire inside the tunnel in combination with the elevated temperature of the smoke itself can result in a high number of fatalities amongst the tunnel users, [2]. Furthermore, in the vicinity of the fire the tunnel structure is heavily damaged and the renovation period can last for a long period of time resulting in tunnel closure and traffic disruption of the route including the particular tunnel. The economic consequences may be very large. Therefore, necessary measures should be envisaged and implemented in order to increase the safety and availability to acceptable levels.

1 REVIEW CURRENT NATIONAL AND INTERNATIONAL REGULATIONS REGARDING THE TRANSPORT OF DANGEROUS GOODS THROUGH ROAD TUNNELS

In Europe, Transport of dangerous goods by road is regulated by the UN Agreement concerning the International Carriage of Dangerous Goods by Road (ADR codes). Most states in the United States and provinces in Canada follow codes in compliance with the United Nations Model Regulations. Australia and Japan have their own codes for defining dangerous goods, although Australia is currently aligning with the United Nations system.

In contrast, the rules and regulations for the transport of dangerous goods in tunnels vary considerably among countries and even within countries. Rules and regulations applying to specific tunnels have been devised in a number of countries. The definition, decision making, responsibility and enforcement are left to local or provincial authorities and politicians, the tunnel owners.

European Parliament and Council adopted the European Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (TERN), in which it is clearly required, when a tunnel is opened for example to the transport of dangerous goods, that a risk analysis should be carried out to establish whether additional safety measures and/or supplementary equipment are necessary to ensure a high level of tunnel safety, [4]. Risk analysis is an important tool that can be helpful for improving and/or optimizing the safety level of road tunnels.

Managing the risks involved with transporting dangerous goods through road tunnels and finding solutions to these complex problems required varied scientific experience and strong financial support. For these reasons, the OECD (Organization for Economic Co-operation and Development) and PIARC (World Road Association) launched a joint research project, which resulted in the Report covering both regulatory and technical aspects of dangerous goods passage through road tunnels, [7,11].

Since EU does not impose a methodology, member states are required to develop, at national level, their own detailed methodology for their country. Many European countries adopted the requirement for all their tunnels with the goal to have a comparable and uniform safety standard for all tunnels within the TERN. Different risk models have been developed by the scientific community and are discussed in the literature, however in many European countries (e.g. Austria, Switzerland, France, and Greece) the QRAM (Quantitative Risk Assessment Model), which was proposed jointly by PIARC and OECD with associated software developed by INERIS, is the one most widely used. A quantitative risk assessment (QRAM) compares level of the risks of transporting dangerous goods through a tunnel versus using an alternative route. A decision support model (DSM) was also developed as part of the research which allows decision makers to combine the results from the QRAM with other relevant data. J. Lundin, L. Antonsson presented a three step method to categorize Swedish road tunnels: the first is a logical decision model , the second is a simplified risk analysis method , finally, expert assessment for risk-based categorization is introduced as a third step, [9]. D. Lees, dealt with tunnel hazards due to fires and explosions from a number of sources including transportation of dangerous goods, traffic accidents, combustion of mechanical or electrical installations, sabotage or terrorism, [8]. A quantitative risk analysis regarding hourly traffic volume and percentage of heavy goods vehicles in order to assess their impact on the risk level of a directional road tunnel were analyzed in [3].

In the Republic of Srpska, the Ministry of Transport and Communications adopted the Rulebook on Minimum Security Requirements for Tunnels, which came into force in 2021, [12]. Regarding the transport of dangerous goods through tunnels, the Rulebook stipulates that the regulations governing the transportation of dangerous goods (ADR) should be applied. The following measures should also be taken conducting a risk analysis, placing appropriate traffic signs, and determining special operational measures aimed at reducing risks during the transportation of dangerous goods through tunnels.

This paper proposes risk charts that are useful for quickly assisting in making decisions on the most appropriate traffic control strategies

2 CATEGORIZATION OF TUNNELS ACCORDING TO ADR

The categorizing of tunnels are based on three main risks which can cause fatalities or severe damage to the tunnel construction. These risks, or rather accident scenarios, consist of explosion, release of toxic substance and fire.The main consequences of these hazards and the efficiency of possible mitigating measures, are following [1,11]:

“Large explosions”, where two levels could be distinguished:

“Very large” explosion is the explosion of a full loading of LPG in bulk heated by a fire (Boiling Liquid Expanding Vapour Explosion – BLEVE – followed by a fireball, referred to as “hot BLEVE”). A “very large” explosion would kill all the people present in the whole tunnel or in an appreciable length of tunnel and cause serious damage to the tunnel equipment and possibly its structure.

“Large” explosion is the explosion of a full loading of a non-flammable compressed gas in bulk heated by a fire (BLEVE with no fireball, referred to as “cold BLEVE”). The consequences of a “large” explosion would be more limited, especially regarding damage to the tunnel structure.

“Large toxic gas releases” can be caused by leakage from a tank containing a toxic gas (compressed, liquefied, dissolved) or a volatile toxic liquid. It would kill all the people near the release zone and in the area where the ventilation (natural or mechanical) would push the gas. A part of the tunnel may be protected but it is not possible to protect the whole tunnel, especially in the first minutes after the accident.

“Large fires” could have more or less important consequences (a certain number of victims and limited to serious damage to the tunnel) depending on the tunnel geometry, traffic and equipment.

From the above assumptions, a system with five groupings can be derived:

The order of these hazards: explosion /toxic release/ fire, corresponds to the decreasing consequences of an accident and the increasing effectiveness of the possible mitigating measures. From the above assumptions, a system with five groupings is derived, ranked A to E in order of increasing restrictions concerning goods permitted in tunnels, Table 1. Grouping A is the largest category. It contains all loadings which are authorized for road transport, including the most dangerous ones. Grouping E is the most restrictive one, containing only those loadings which do not require a special marking on the vehicle, i.e. the least dangerous ones.

Decisive factors for restrictions on the transportation of dangerous goods include the properties of the goods, the type of containment, and the amount being transported. The ADR regulations do not explicitly define terms such as “very large explosion”, “large explosion”' or “large toxic emissions", etc.

Table 1 Grouping goods in Tunnel category, [11]

Grouping A	All dangerous goods loadings authorised on open roads.
Grouping B	All loadings in grouping A except those which may lead to a very large

	explosion (“hot BLEVE” or equivalent).
Grouping C	All loadings in grouping B except those which may lead to a large explosion (“cold BLEVE” or equivalent) or a large toxic release (toxic gas or volatile toxic liquid).
Grouping D	All loadings in grouping C except those which may lead to a large fire.
Grouping E	No dangerous goods (except those which require no special marking on the vehicle).

3 A RISK ASSESMENT

Damage that can occur during the transportation of dangerous goods through the tunnel can be expressed by the loss of human life, environmental pollution, tunnel damage and economic loss. The types of harm are the same for vehicles transporting dangerous goods as for other vehicles, the difference is only expressed in the level of damage [6].

Harm to people (including injuries as well as fatalities) is the most important hazard type relating to the assessment of the transport of dangerous goods through tunnels. The most commonly used indicator for the quantitative assessment is statistical fatalities. The impact on the environment may also be relevant to the transport of dangerous goods. In the event of an accident in the tunnel, although the release of hazardous material may be confined to a narrow area within the tunnel, the consequences can still affect the surrounding environment, such as through soil pollution, groundwater contamination, and habitat destruction. Two types of economic loss may be distinguished: the (direct) capital losses due to the damage caused by the event, and (indirect) economic losses due to the tunnel closure. The risks linked to these types of harm can be analyzed either quantitatively (focusing primarily on the interaction and interdependence of events) or qualitatively (which allows for the calculation of characteristic risk values), or both (in cases where data is insufficient, a combination of qualitative and quantitative components might be used).

To managing the risks involved with transporting dangerous goods through road tunnels, it is necessary to perform a risk assessment. The risk assessment is a tool to identify the hazards and analyze the probability and magnitude of damage in order to obtain a quantifiable risk indicator. Figure 2 illustrates the typical procedure for a risk assessment [6,13]. The risk assessment procedure (presented by PIARC 2008, UNECE 2008) includes the stages:

- risk analysis,
- risk evaluation,
- and risk reduction.

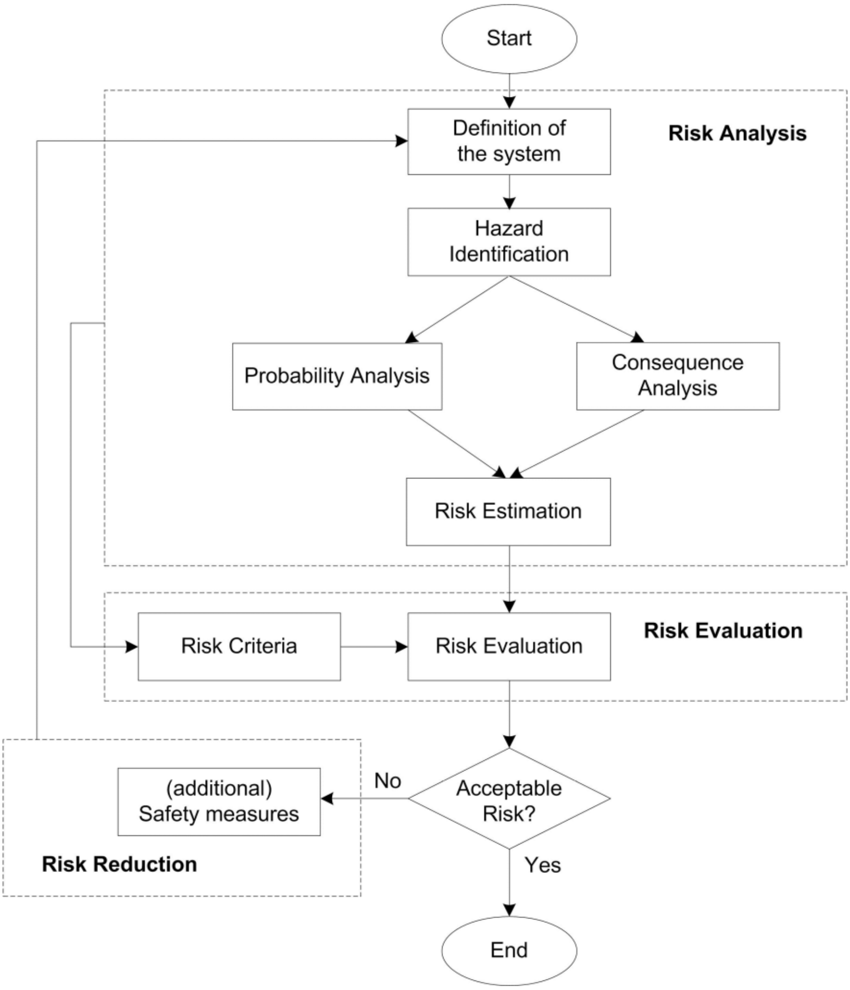


Figure 2 Risk assessment flowchart [6,13]

The first step in the risk analysis stage is the description of the tunnel itself, including its geometrical and traffic characteristics, as well as operating procedures and emergency planning. In the hazard identification step, all potential hazards that may result in particular risks are identified and categorized. For each potential risk, a frequency and consequence analysis is performed resulting in risk estimation. Following the risk estimation step, a risk evaluation is performed by comparing the estimated risks with the established risk criteria. In case the risk criteria are satisfied, the risk level is acceptable. On the other hand, if the risk exceeds the acceptable level, additional measures are proposed, and the risk assessment procedure is repeated until the risk level meets the acceptable criteria, [13].

3.1 The Quantitative Risk Assessment Model (QRAM)

The QRAM aims to quantify the risks associated with the transport of dangerous goods on given road system routes, as well as to compare one route including a tunnel with an alternative route in open space. The components relevant to the development of the QRA model are as follows:

- indicators,
- accident scenarios,
- assessment of the probability of an accident,
- determination of physiological consequences, structural and environmental damage,
- determination of physiological consequences, structural and environmental damage,
- assessment of consequences for people,
- uncertainty/sensitivity analysis,
- validation.

3.2 Indicators

The consequences of an accident are fatalities, injuries, destruction of buildings and structures and damage to the environment. The QRAM produces indicators which characterise the following risk aspects:

Societal risk: To describe social risk, F/N curves are calculated that illustrate the relationship between accident frequency and accident severity.

Individual risk indicators refers to the risk of fatalities or injuries to the local population due to an incident occurring. Individual risk is expressed as a frequency per year.

Structural damage (rough estimation).

Environmental damage (rough estimation).

3.3 Accident scenarios

A complete risk assessment related to the transport of dangerous goods could require consideration of many variables: variety of hazardous materials, variety of weather conditions, variety of types of accidents, sizes of breaches, vehicles fully or partially loaded, etc. Since all circumstances are impossible to consider, simplifications have to be made.The model is based on consideration of 13 accident scenarios, which have been selected so as to satisfy the requirements of examining the three major dangers which may cause numerous victims or serious damage to the tunnel structure including explosions, release of toxic gas or volatile toxic liquid and fire. It also considers the accidents frequencies (based on historical data), the physical consequences of the accidents, and the effects of heat and smoke, Table 2. The use of QRAM software for conducting tunnel categorization according to ADR agreement can be made by assigning the proper scenarios to each tunnel category.

Table 2 Scenarios representative of each grouping in the QRA model, [13]

	Scenario	**Danger**	**Tunnel Categories**				
			A	B	C	D	E
1	HGV fire 20 MW	Medium Fire	√	√	√	√	
2	HGV fire 100 MW	Large fire	√	√	√		
3	BLEVE of LPG in cylinder	Small Explosion	√	√	√	√	

4	Motor spirit pool fire	Large Fire	√	√	√		
5	VCE of motor spirit	Medium Size Explosion(1)	√	√	√		
6	Chlorine release	Large Toxic Release	√	√			
7	BLEVE of LPG in bulk	Very Large Explosion	√				
8	VCE of LPG in bulk	Very Large Explosion	√				
9	Torch fire of LPG in bulk	Very Large Fire(2)	√				
10	Ammonia release	Large Toxic Release	√	√			
11	Acrolein in bulk release	Large Toxic Release	√	√			
12	Acrolein in cylinder release	Medium Size Toxic Release	√	√	√	√	
13	BLEVE of carbon dioxide in bulk (not including toxic effects)	Large Explosion	√	√			

(1) VCE of motor spirit including the realization of a flash fire is considered to be equivalent to a large fire.

(2) Torch fire of LPG in bulk resulting in a very large fire is considered to be equivalent to a very large explosion since the fire size will cover almost the full tunnel length.

As we can see from the Table 2, only a limited number of scenarios are taken into account. The first two scenarios relate to fires of medium and important intensity involving heavy goods vehicles without dangerous goods. These scenarios represent a serious risk in tunnels. The other scenarios involve dangerous goods.

3.4 Assessment of the probability of an accident

The purpose is to determine frequencies of occurrence of the chosen scenarios depending on the section of the route considered. For this purpose, the route must be subdivided into homogenous sections in terms of road elements, traffic, dangerous goods transported, environment and weather conditions. This must be done by the user of the model, who also has to provide and prepare the necessary input data.

3.5 Determination of physiological consequences, structural and environmental damage.

The translation of the physical consequences into physiological ones is generally performed by means of probit functions. Probit functions indicate the relationship between the concentration of a substance in the air, the exposure time and the effect on (in this case) humans.

Structural damage represents: collapse or structural integrity problems, damage of tunnel roadway, strength loss of common structural material, failures of tunnel auxiliary equipment caused by high temperatures etc.

The main environmental impact of accidents with hazardous materials in the tunnel is the contamination of the atmosphere, water and soil.

3.6 Assessment of consequences for people (open and tunnel sections).

Extensive calculations provide individual risk data and F/N curves for selected scenarios and for different types of transport.

3.7 Uncertainty/sensitivity analysis.

Deterministic analysis involves uncertainties. Different parameters should be tested to assess their effects (variation in travel speed, variation in warning systems, variation in individual occupant response time, etc).

3.8 Validation

This step in the development of the QRAM is necessary to test the developed model by persons not involved in the model-building process, but familiar with system behaviour, risk assessment and computer models.

4 TUNNEL CATEGORIZATION PROCEDURE

The proposed methodological approach for tunnel categorization, according to ADR agreement using QRAM software, is presented in Figure 3.

In the first step of “System Definition”, an extensive and detailed description of the necessary inputs for QRAM software should be made regarding the tunnel itself along with the route including the tunnel and the alternative routes. Special attention should be given in the traffic characteristics (the percentage of traffic distribution during the annual average day and the percentage of heavy good vehicles, traffic distribution of vehicles carrying dangerous goods during the annual average day).

In the next step, the number and range of time periods (TP) when traffic is allowed through the tunnel and alternative routes should be set. Also, in this step, the percentage of ADR vehicles that will use an alternative route in case of a ban on passing through the tunnel during their agreed travel time schedule should be assumed, while the other mentioned vehicles will move the agreed travel time schedule to the closest time period in which they are allowed to pass through the tunnel.

Following the time periods definition, the assignment of tunnel categories (TC) to each time period (TC/TP) is being initiated in a loop procedure. The five (A, B, C, D and E) possible tunnel categories are assigned to the three time periods in 65 proposed combinations.

The next step includes the risk analysis calculations by using the QRAM software. In each of the aforementioned QRAM software calculations, the Risk in terms of Expected Value is calculated for each of the 13 scenarios for the tunnel, for the route including the tunnel and for the alternative route. The Expected Value represents the annual expected fatalities from the consequences of accidents due to the involvement of the carried dangerous goods.

If the risk through tunnel R_T is acceptable, it is stored in the database. If not, then the risk through an alternative route R_{AR} is examined.

Once all possible TC/TP configurations have been examined, the necessary data of the accepted configurations have been saved in order to be used in the “Cost Benefit” Analysis step, where the final tunnel categories assigned to the different time periods will be finalized and the tunnel categorization will be completed.

In the final step “Cost Benefit Analysis” the various contributors saved in the step “Database” are measured in monetary values.The expected life cycle cost derived by tunnel categorization is calculated as the sum of the costs of safety measures and the cost of residual risk. At the end, the TC/TP configuration with the minimum life cycle cost is selected and the tunnel categorization process is complete.

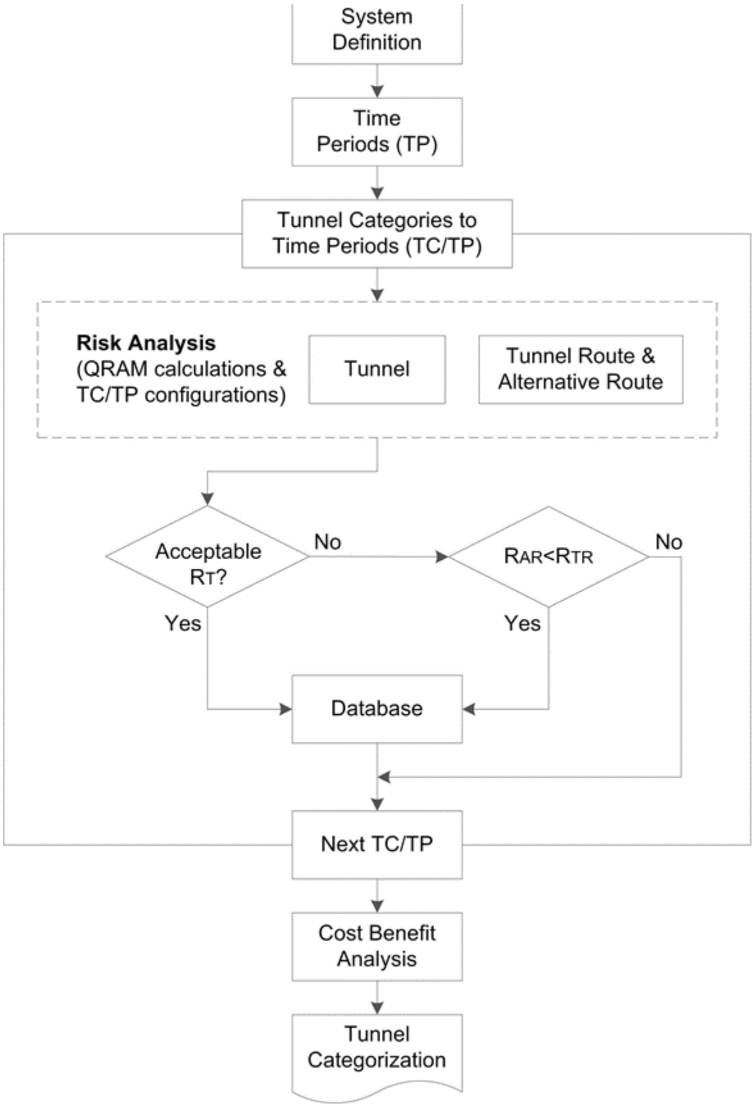


Figure 3 Tunnel categorization procedure [13]

5 THE DECISION SUPPORT MODEL (DSM)

Decision Support Model (DSM), which incorporates political aspects, is clearly separated from the QRAM, which is purely technical. The DSM uses the output from the QRAM and other information supplied by the decision maker as shown in Figure 4.

In the decision-making process regarding which groupings are permitted in tunnels, it must be considered that goods not allowed in the tunnel should be transported via an alternative route One of the primary aims for the decision on which grouping to permit in a tunnel is to minimize the risk to human life, but there are other factors that need to be taken into account. The features that are evaluated and weighted by a decision support model (DSM) are following [11]:

- Injury and fatality risks to road users and the local population using the indicators from the QRAM.
- Material damage due to possible accidents on tunnel or alternative route.
- Environmental impact due to an accident on tunnel or alternative route.
- Direct expenses (investment and operational cost of tunnel risk reduction measures as well as possible additional costs in the transport of dangerous goods).
- Inconvenience to road users due to a possible accident (time lost during repair works after an incident in the tunnel).
- Annoyance to local population (environmental impact of dangerous goods traffic, with the exclusion of possible accident consequences, but possibly including psychological impact).

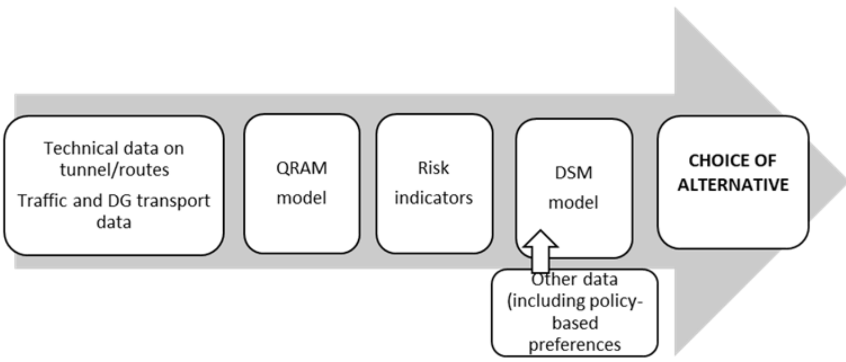


Figure 4 Structure of the decision process

In the decision-making process, must determine which characteristics are relevant and how they should be weighted against each other. A computer program was developed that allows the mentioned characteristics to be taken into account in a rational way.

CONCLUSIONS

Safety measures to be applied in road tunnels are based on a systematic consideration of all aspects including: tunnel infrastructure, works in tunnels, users and vehicles. If there are additional characteristics which must be taken in account, such as the transport of dangerous goods through tunnel, a detailed risk analysis must be carried out to determine if there is a need for additional safety measures and/or additional equipment to ensure a high level of tunnel safety. Based on the risk analysis of the transport of various dangerous goods through tunnels, their categorization is carried out. Categorization is a complex process where it is necessary to address the risks in the tunnel, the risks along the alternative route for transports considered to be restricted from the tunnel and what risk reducing measures that are practically applicable. A Quantitative Risk Assessment model (QRAM) was developed by international consultants in order to provide risk indicators which can be used in a decision support model (DSM) to compare a route including one or several tunnels with alternative open routes, and possibly with risk acceptance criteria. The DSM model determines which features are relevant and how they should be weighted relative to each other. A computer program has been developed that allows the mentioned characteristics to be taken into account in a rational way. Based on the risk analysis for the transport of dangerous goods through tunnels, the categorization of tunnel is done (A - E), regulating the types of dangerous goods to be allowed to go through the tunnel, in order to avoid any hazards with major consequences.

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