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Methodological approaches for tunnel classification according to ADR agreement

N. Vagiokas[1], A. Bletsas[1], R.M.L. Nelisse[2]

[1]*ENALOS Ltd, Athens, Greece*

[2]*TNO, Delft, The Netherlands*

ABSTRACT: Past tunnel fire accidents have revealed the high impact of consequences on human life and infrastructure. Furthermore, accidents involving thermal radiation, overpressure and toxicity have even larger consequences when dangerous goods are involved. Therefore, special consideration should be given to the proper planning of tunnel operation regarding safe transportation of dangerous goods. 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. Furthermore, according to Directive 2004/54/EC a risk analysis should be performed before any regulations and requirements regarding the transportation of dangerous goods through a tunnel are defined or modified. In the present study a brief description of the quantitative risk assessment model (QRAM) is given. QRAM is used in tunnel risk analysis for the passage of dangerous goods and can satisfy the regulatory framework for tunnel categorization. The results of the present study include appropriate methodological approaches using QRAM in order to conclude in tunnel categorization regarding transportation of dangerous goods through road tunnels.

1 Introduction

Tunnelling industry is expanding over time, since population growth restrict the available surface area uses. In the last decade numerous road tunnel projects have been completed and several others are in progress throughout the world. Except from the fact that road tunnels do not use surface area, they also minimize the time needed to travel from an origin to a destination. Reducing the distance and the time travelled have also other benefits including decreased emissions to the environment, reduced fuel consumption for the users, etc.. In order for the society to exploit the full range of advantages that road tunnels introduce, the safety level in combination with the availability level of operating a road tunnel and the life-cycle costs involved, should meet a minimum set of acceptable criteria.

Past 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 who are exposed to the aforementioned injury factors (Beard et al 2005). 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, as was the case with the closure of the Mont Blanc tunnel. Therefore, necessary measures should be envisaged and implemented in order to increase the safety and availability to acceptable levels. These measures will contribute to the prevention of trigger events resulting in accidents, therefore decreasing accident rates and frequency of accident occurrence. Also, these measures will result in optimum tunnel incident management by limiting potential consequences and necessary time for the tunnel to be given into traffic again.

The consequences of tunnel fires mainly depend on the maximum fire power output. Small fires in the range of 2.5MW to 8MW result from fires spread to up to 3 passenger cars, while medium size fires from 20MW to 50MW result from fires burning a bus or a truck without burning the goods carried by the truck. Large fires in the range of 100MW result from heavy good vehicles involving their freight, while very large fires of up to 200MW may result from heavy good vehicles involving their dangerous goods load (PIARC 1995). The consequences of small fires are usually negligible, while in case of medium fire size several fatalities may occur and a tunnel wash and minor equipment replacement may be needed. In case of large fires, it is very probable to have a substantial number of fatalities and severe structural damage. As a result of very large fires resulting from dangerous goods involvement, the maximum number of possible fatalities is expected along with local collapse of the tunnel structure. Therefore, although very large fires are very rare events compared in terms of frequency with small and medium size fires, risk aversion is the main contributor to the decision making process for mitigating the probability and the consequences of such events.

Several risk analysis methodologies have been developed by the scientific community (Bubbico et al 2009, Holicky 2009, Nathanail et al 2010, Schubert et al 2012), in order to identify potential hazards and specify appropriate safety measures for reaching acceptable levels of tunnel safety. Furthermore, European Union member states have developed specific methodologies for tunnel risk analysis based on the aforementioned scientific results. These methodologies include the Austrian tunnel risk model TuRisMo, the Dutch QRA-tunnels, the French specific hazard identification, the Italian risk analysis for road tunnels, the OECD/PIARC QRA model, etc. (PIARC 2008, Rijkswaterstaat 2012). Some of these methodologies consider also the transportation of dangerous goods. In one way or the other, almost all methodologies considering transportation of dangerous goods include the use of QRAM software. The development of QRAM software has been jointly organized by the OECD and PIARC with significant contribution from the European Commission (OECD/PIARC 2001).

2 Methodology

The use of QRAM software is broadly accepted by almost all countries that have in their national legislative framework the obligation of conducting risk analysis studies for the transportation of dangerous goods through road tunnels. This software includes the modeling of 13 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 (ADR 2013). These scenarios are described in table 1.

Table 1. Main characteristics of the 13 selected scenarios

Scenario	Description	Tank capacity	Breach size [mm]	Mass flow rate [kg/s]
1	HGV fire 20MW	-	-	-
2	HGV fire 100MW	-	-	-
3	BLEVE of LPG in cylinder	50 kg	-	-
4	Motor spirit pool fire	28 tonnes	100	20.6
5	VCE of motor spirit	28 tonnes	100	20.6
6	Chlorine release	20 tonnes	50	45
7	BLEVE of LPG in bulk	18 tonnes	-	-
8	VCE of LPG in bulk	18 tonnes	50	36
9	Torch fire of LPG in bulk	18 tonnes	50	36
10	Ammonia release	20 tonnes	50	36
11	Acrolein in bulk release	25 tonnes	10	24.8
12	Acrolein in cylinder release	100 litres	4	0.02
13	BLEVE of carbon dioxide in bulk (not including toxic effects)	20 tonnes	-	-

HGV: Heavy Goods Vehicle, BLEVE: Boiling Liquid Expanding Vapour Explosion, LPG: Liquefied Petroleum Gas, VCE: Vapour Cloud Explosion.

In figure 1 the necessary steps for conducting a risk assessment are presented (PIARC 2008, UNECE 2008). The risk assessment procedure includes the stages of risk analysis, risk evaluation and risk reduction. The first step of the risk analysis stage is the description of the tunnel itself, where the geometrical and the traffic characteristics along with the operating procedures and the emergency planning are described. Afterwards, 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 risk estimation with the risk criteria. In case the risk criteria are satisfied, the risk level is acceptable. On the other hand, where the risk is above the acceptable level, additional measures are proposed and the procedure of risk assessment is being performed again until the risk falls in levels where acceptable criteria are met. The QRAM software is broadly accepted as a scientific reliable tool for conducting the risk analysis stage for assessing risks that arise from the transportation of dangerous goods through road tunnels.

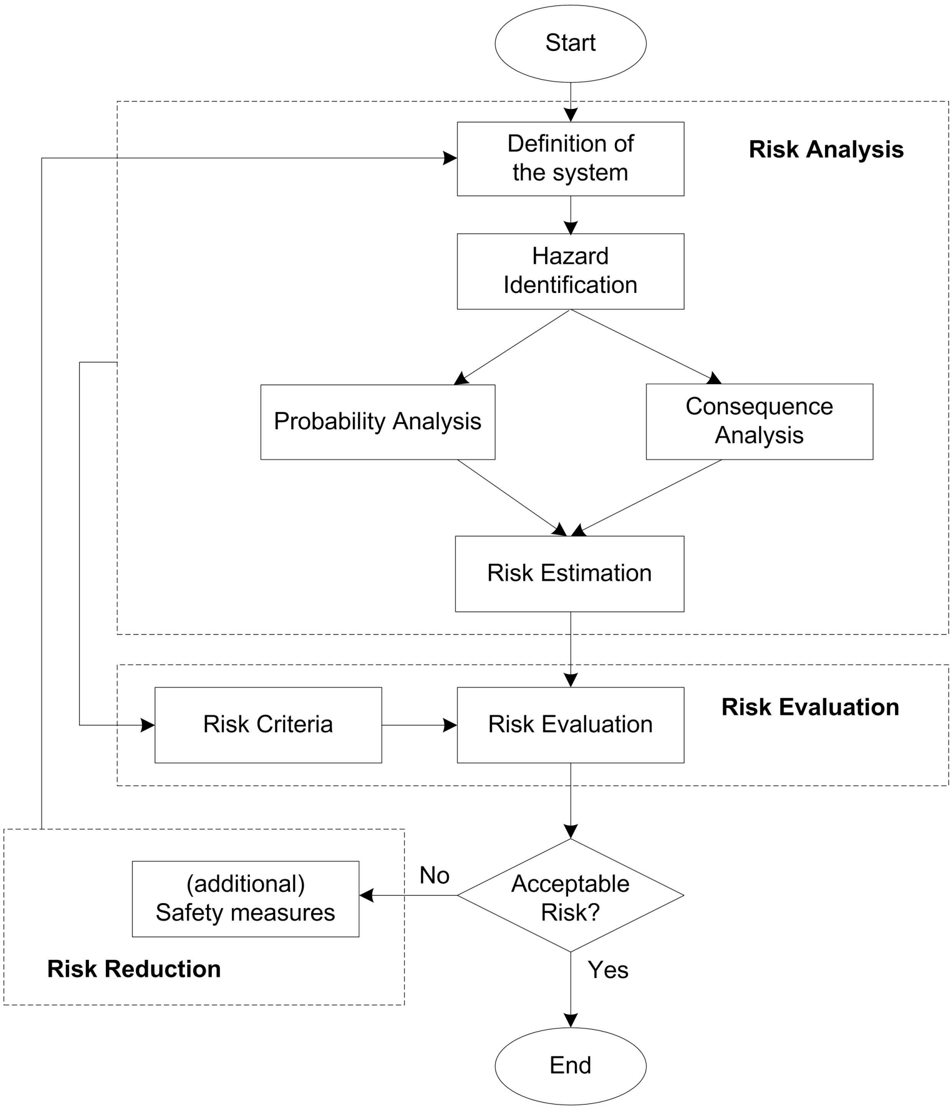

Figure 1. Risk assessment flowchart

According to the EU Directive concerning minimum safety requirements for tunnels in the Trans-European Road Network (Directive 54/2004/EC), a risk analysis should be performed before the regulations and requirements regarding the transportation of dangerous goods through a tunnel are defined or modified (Article 13). Furthermore, according to the ADR agreement, when applying restrictions to the passage of vehicles carrying dangerous goods through tunnels in order to assign the tunnel to one of the five categories (A, B, C, D and E) account should be taken of the tunnel characteristics, risk assessment including availability and suitability of alternative routes and modes and traffic management consideration. The five tunnel categories are:

- *Tunnel category A*: no restrictions for the transport of dangerous goods.
- *Tunnel category B*: restriction for dangerous goods which may lead to a very large explosion.

- *Tunnel category C*: restrictions for dangerous goods which may lead to a very large explosion, a large explosion or a large toxic release.
- *Tunnel category D*: restrictions for dangerous goods which may lead to a very large explosion, a large explosion, a large toxic release or a large fire.
- *Tunnel category E*: restrictions for all dangerous goods other than UN numbers 2919 (non-fissile radioactive material), 3291 (clinical waste), 3331 (fissile radioactive material), 3359 (fumigated cargo transport unit) and 3373 (biological substances).

The categorization should be based on the assumption that in tunnels there are three major dangers which may cause numerous victims or serious damage to the tunnel structure. These dangers include explosion, release of toxic gas or volatile toxic liquid and fires. The use of QRAM software for conducting tunnel categorization according to ADR agreement as proposed by the developers of the QRAM software can be made by assigning the proper scenarios to each tunnel category. In tunnel category A the proposed scenarios to be assigned are 3 to 13, in tunnel category B the proposed scenarios are 3 to 6 and 10 to 11, in tunnel category C the proposed scenarios are 3 to 5 and 12, and in tunnel category D the proposed scenarios are 3 and 12.

3 Results

The methodological approach of the present study includes the proposed procedure and the steps that should be followed in order to categorize the tunnel according to the requirements imposed by ADR agreement.

The characterization of the 13 QRAM scenarios as very large explosion, large explosion, large toxic release and large fire results in the following representation of each scenario in the tunnel categories, as presented in table 2.

Table 2. QRAM software scenarios representation in each tunnel category

	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.

In the proposed representation of QRAM software scenarios to each tunnel category, the first two scenarios which refer to HGV fires of 20MW and 100MW are assigned to medium and large fires respectively. These types of fires can result from the involvement of some flammable dangerous goods categorized in ADR classes 4.1 flammable solids, self-reactive substances and solid desensitized explosives, 4.2 substances liable to spontaneous combustion and 4.3 substances which, in contact with water, emit flammable gases.

In figure 2 the proposed methodological approach for tunnel categorization, according to ADR agreement using QRAM software, is presented. 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 concerning the percentage of traffic distribution during the annual average day and the percentage of heavy good vehicles. Furthermore, detailed data should be collected for the traffic distribution of vehicles carrying dangerous goods during the annual average day along with the synthesis of dangerous goods.

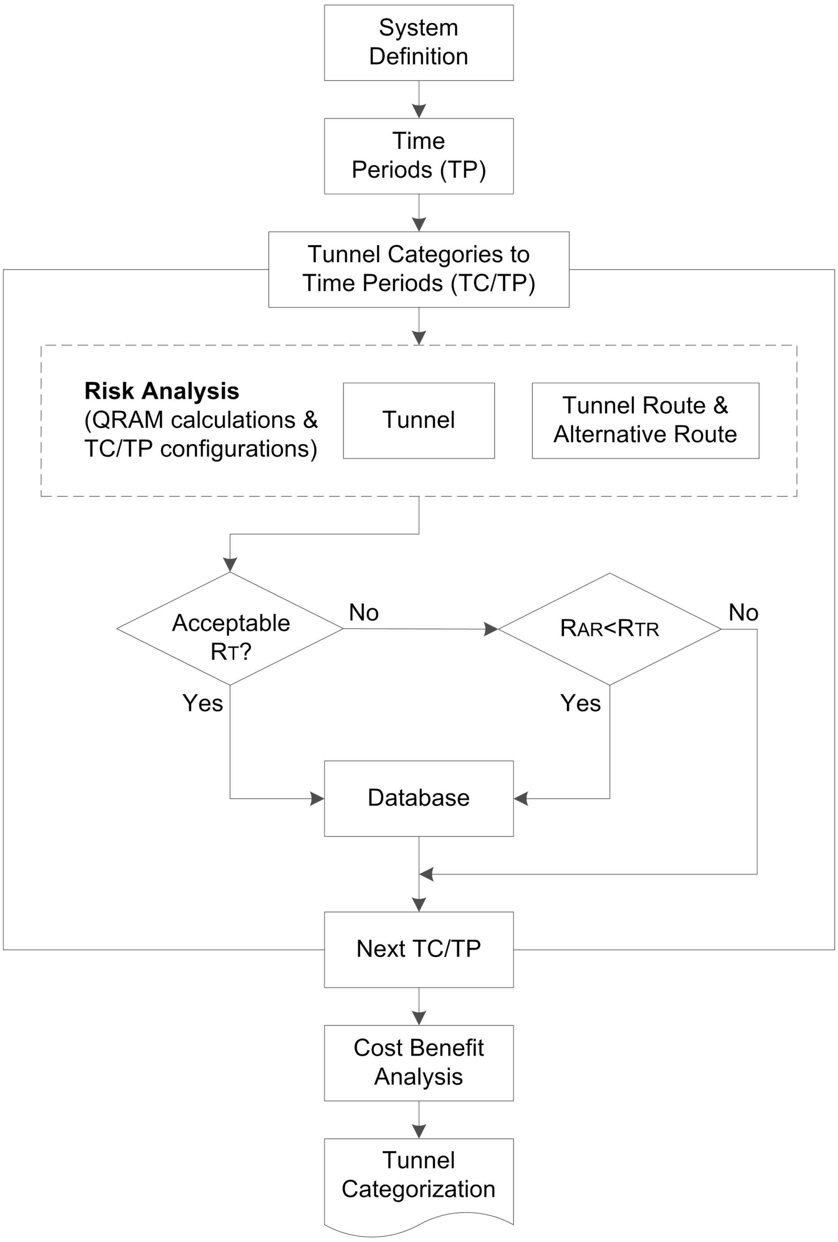

Figure 2. Tunnel categorization procedure

In the next step, the number of time periods should be set and their range should be given. The maximum number of time periods (TP) are limited to three according to QRAM software possibilities, while the entire time range of each time period does not need to be consecutive (e.g. TP1: 21:00 - 06:00, TP2: 06:00-08:00 & 15:00-17:00, TP3: 08:00-15:00 & 17:00-21:00). A rule of thumb for establishing the three time periods (quiet, normal, peak) is to determine the maximum hourly percentage of annual average daily traffic (AADT) during a 24h hourly distribution, and divide by three. The quiet period will be established by the hours with traffic volumes within the range of 0 to 1/3 of the maximum hourly percentage of AADT, the normal period will be established by the hours with traffic volumes within the range of 1/3 to 2/3 of the maximum hourly percentage of AADT, and the remaining hours will form the peak period. Also, in this step it should be established by sound assumptions the percentage of vehicles carrying dangerous goods that will use the alternative route in case their passage through the tunnel is prohibited during their arranged trip time-schedule, while the rest of the aforementioned vehicles will shift their arranged trip time-schedule to the closest time period that their passage through the tunnel is allowed.

Following the time periods definition, the assignment of tunnel categories 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 proposed combinations are derived by all possible combinations including only one or two tunnel categories per combination. Furthermore, after proper examination of traffic pattern flows of vehicles carrying dangerous goods, extra TC/TP configurations including escorting of vehicles carrying dangerous goods in certain time periods can be added to the examined combinations.

The next step includes the risk analysis calculations by using the QRAM software. The necessary inputs have been determined and finalized in the first two steps of 'System Definition' and 'Time Periods'. The calculations are being performed once for the tunnel itself and once for the route including the tunnel and the alternative route. 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.

After the first configuration, where tunnel category A has been assigned in all three time periods (TC/TP_1) the Expected Value of the tunnel itself (R_T) is derived and compared to the acceptance criteria. If the acceptance criteria are met, then TC/TP_1 is saved to the 'Database' and the process continues to the next TC/TP configuration. In case R_T is above the acceptable threshold limit value, the Expected Value of the route including the tunnel (R_{TR}) is compared with the Expected Value of the alternative route (R_{AR}). If R_{AR} is less than R_{TR} within a statistical significant evaluation in order to account for uncertainties, the alternative route is selected for the particular TC/TP configuration and saved to the 'Database', while the process continues. If R_{AR} is not statistically significant less than R_{TR}, the particular TC/TP configuration is rejected and the process continues.

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 of 'Cost Benefit Analysis' the various contributors saved in the 'Database' step, 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. The total cost of safety measures is equal to the sum of the initial cost of installation of the safety measures, the maintenance cost and the operation cost minus the salvage cost of the safety measures installations. The total cost of residual risk is equal to the sum of the human impact cost, the cleaning and rehabilitation of accident scene cost, the evacuation of the nearby population cost, the public property damage cost, the business interruption cost, the freight loss and vehicle damage cost and the cost of traffic delay (Vagiokas 2012). Furthermore to the aforementioned indicative costs, environmental impact and other costs may be included in the cost benefit analysis (Nelisse 2012). At the end, the TC/TP configuration with the minimum life cycle cost as described above is selected and the tunnel categorization process is complete.

4 Conclusions

In the present study, a methodological approach has been developed and presented using the QRAM software for determining optimum tunnel categorization according to ADR Agreement requirements. Although due to the total number of TC/TP configurations, where certain tunnel categories are assigned to specific time periods, the entire procedure may be considered time consuming, this is not the case since the majority of data entries are being performed once for all different TC/TP configurations and only the synthesis and the traffic volume of vehicles carrying dangerous goods are entered in the QRAM software for each TC/TP configuration.

The use of cost benefit analysis in the proposed tunnel categorization process has multiple advantages for all stakeholders. Member states can use the proposed methodological approach for tunnel categorization as decision support tool in order to justify the assigning of different tunnel categories to different time periods. Furthermore, the tunnel manager can use the proposed methodology in order to justify additional operating measures including escort of vehicles carrying dangerous goods and its related costs for enhancing safety levels during specific time periods and cooperate with administrative authorities for their financing.

Therefore, the proposed methodological approach for tunnel categorization using the QRAM software is recommended as a sound justified decision support tool to be used by Member States in the implementation of European Directive enforcing ADR Agreement in their territories.

5 References

ADR 2013. European Agreement Concerning the International Carriage of Dangerous Goods by Road, Economic Commission for Europe, Committee on Inland Transport, United Nations, New York and Geneva.

Beard, A., Carvel, R. 2005. The handbook of tunnel fire safety, Thomas Telford, London.

Bubbico, R., Di Cave, S., Mazzarotta, B., Silvetti, B. 2009. Preliminary study on the transport of hazardous materials through tunnels. Accident Analysis and Prevention 41, 1199-1205.

Directive 54/2004. Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network, Official Journal of the European Union, L 167, pages 39 – 91.

Holicky, M. 2009. Probabilistic risk optimization of road tunnels. Structural Safety 31, 260-266.

Nathanail, E.G., Zaharis, S., Vagiokas, N., Prevedouros, P.D. 2010. Risk assessment for the transportation of hazardous materials through tunnels. Transportation Research Record 2162, 98-106.

Nelisse, R.M.L., Vrouwenvelder, A.C.W.M., 2012. Assessment model for the transport of dangerous goods through road tunnels, Proceedings of the Fifth International Symposium on Tunnel Safety and Security, New York, USA.

OECD/ PIARC, 2001. Safety in Tunnels: Transport of Dangerous Goods through Road Tunnels, OECD, Paris.

PIARC, 1995. Fire and Smoke Control in Road Tunnels, PIARC Committee on Road Tunnels (C5), Paris.

PIARC, 2008. Risk Analysis for Road Tunnels, PIARC Technical Committee C3.3 Road tunnel operation, Paris.

Rijkswaterstaat, 2012. Gebruikershandleiding QRA-tunnels 2.0. Ministerie van Infrastructuur en Milieu, The Netherlands.

Schubert, M., Hoj, N.P., Ragnoy, A., Buvik, H. 2012. Risk assessment of road tunnels using Bayesian networks. Procedia – Social and Behavioral Sciences 48, 2697-2706.

UNECE, 2008. General guideline for the calculation of risks in the transportation of dangerous goods by road. 84th and 85th sessions of WP 15 on the Transportation of Dangerous Goods, 1-17.

Vagiokas, N. 2012. Developing a methodology for determining design and operating requirements for contracting tunnel works. International Symposium: Practices and Trends for Financing and Contracting Tunnels and Underground Works, Athens 22-23 March 2012, Greece.