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Quantitative operational risk analysis for dangerous goods transportation through cut and cover road tunnels

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ABSTRACT: This paper deals with risk analysis in cut and cover road tunnels. The research question explored is whether dividing a long tunnel into shorter sections would affect the safety when dangerous goods are allowed through the tunnel. In order to conclude the OECD /PIARC QRA Model quantitative risk analysis tool was used. Initial findings reveal that there is no evidence of increase in safety from dividing a long urban cut and cover tunnel in smaller parts with open air areas in between. However, the overall safety depends to a great extend on the specific characteristics of each particular case, since there are many factors that influence the overall safety of road tunnels. Therefore it is concluded that risk analysis using systemic approach is crucial for any road tunnel.

1 INTRODUCTION

The increasing number of road tunnels is raising upfront an endogenous problem, which is the severity of accidents that may occur. Accidents in tunnels may lead to heavy consequences for users, the infrastructure itself as well as the environment. Especially when transportation of dangerous goods (DGs) is allowed through a road tunnel, the consequences of a possible accident take the form of a societal risk due to its potential extensive impact.

Transportation of dangerous goods through road tunnels bears, in almost all cases, a vivid debate towards the sufficiency of safety procedures and the cost – benefit analysis for letting them pass, or not, through the tunnels. Although the European agreement concerning the international carriage of dangerous goods by road (ADR) defines explicitly the kinds of goods that can be considered dangerous, very often Heavy Goods Vehicles that do not carry dangerous goods but may lead to significant fires (greater than 20MW) when involved in an accident are also considered as dangerous, since fire is the most significant risk in road tunnels.

This research explores a particular occasion where dangerous goods, in the broad sense, have to pass through cut and cover road tunnels. The question explored is whether dividing a long tunnel into more than one, shorter sections at the design phase would lead to higher or lower overall safety as the open area dividing the sections would on one hand relieve the impact of a DGs accident inside the tunnel but on the other hand would share this impact to the surrounding environment of the tunnel. The research question is of great importance, especially for urban tunnels (most of the times cut and cover technique is possible and chosen in such areas) where the surrounding environment of the tunnel consists of other roads, buildings and thus high concentration of population.

The comparison among different cases has been implemented by using the OECD /PIARC QRA Model, which is probably the mostly accepted simulation tool for transportation of DGs through road tunnels. Initial findings indicate that for twin bore tunnels 3km long, the “cutting” of a tunnel to smaller sections with open areas in between the sections would neither increase nor decrease the overall safety. Thus, the decision on the preferable design approach should be evaluated on a case by case basis, as well as take into account other considerations for the operation of the tunnel and the environment. That is, a systemic approach in road tunnels safety is necessary.

The rest of this paper is organised as follows: The second section presents risk analysis in road tunnels and highlights the importance of such an analysis in the conceptual design stage of a tunnel. The third section is divided in three subsections dealing with the research question, the examined cases description and the QRA model results. The paper concludes with a section which summarises the findings of the research and reveals the need for a systemic approach as far as tunnel safety is concerned.

2 RISK ANALYSIS IN ROAD TUNNELS

Risk management entails the processes of risk identification, analysis, mitigation and follow up and for each process a set of potential tools exist to aid risk managers in their work (Leopoulos et al., 2006). Specifically for risk analysis, simulation is one of the mostly used tools (Rentizelas et al., 2007; Tziralis et al., 2009). In its bare essence, risk analysis answers the fundamental questions of what can go wrong, how likely it is, as well as what are the consequences (Apostolakis, 2004) and it can be carried out in a qualitative or a quantitative way or as a combination of both. In case of a quantitative analysis, probabilities of accidents and their consequences are estimated. Quantitative risk analysis methods were initially developed in the nuclear industry in the early 1970's (Rasmussen, 1975). After two severe accidents with hazardous materials in chemical plants (Bhopal, Seveso) the quantitative risk analysis methods were adjusted to chemical plants in the late 1970's (COVO, 1982), as well.

In the context of road tunnels, risk analysis is considered to be an important tool which can be used to improve and optimize safety. Hence the European Directive 2004/54/EC entitled "minimum safety requirements for tunnels in the trans-European road network" requires the implementation of a risk analysis in cases such as the opening of a road tunnel to dangerous goods or for the evaluation of different mitigation measures than proposed by the Directive (PIARC, 2008).

Quantitative risk analysis in road tunnels produces a quantified risk expressed as an individual risk (e.g. fatality rate per tunnel kilometer) and a societal risk arising from the public's aversion to high numbers of fatalities in a single accident (Khoury and Molag, 2005). A common way to describe societal risk is to calculate F/N curves that illustrate the relationship between accident frequency and accident severity (Knoflacher, 2002). A broad range of quantitative methods are available, thus the choice of the methods should be done by considering the respective advantages/disadvantages in the context of a specific situation (PIARC, 2008). Besides, the EU Directive does not indicate the method for performing the risk analysis or the criteria for risk acceptance. Therefore, each country's administrative authority or even each tunnel manager may select the appropriate method of analysis as well as the criteria for risk acceptance (EC, 2004). However, the method that seems to be the most widely accepted by administrative authorities for quantitative risk analysis is the OECD /PIARC QRA Model (QRAM) that has been developed by INERIS, WS-Atkins and the Institute for Risk Research (INERIS, 2005).

The aim of the QRAM is to quantify the risks due to transport of dangerous goods on given routes of the road system and to evaluate the effect of the mitigation measures carried out in a specific road tunnel (Safe-T, 2008). A complete assessment of the risks involved in transporting dangerous goods would require consideration of all kinds of dangerous materials and other general variables such as meteorological conditions. As the coverage of all circumstances is very difficult in practice, simplifications are made. Thus, the QRAM considers 13 accident scenarios which are representative of the groupings of dangerous goods as described in the proposed regulations of PIARC (OECD, 2001) and have been chosen to examine different severe effects such as overpressure, thermal effect and toxity (Knoflacher et al, 2002).

The outcome of the Model is the Individual Risk (expected value of risk) as well as the relevant F/N curves for fatalities and injuries (INERIS, 2005). The evaluation of the safety of a tunnel based on the F/N curves provided by the Model is usually made either on a comparative basis (comparison to alternative routes) or according to the positioning of the F/N curves compared to a threshold of non tolerable risk. In this work, the safety of the examined cases is evaluated with respect to the other option (comparative basis), which is to cut the tunnel in smaller parts.

It must be mentioned that quantitative risk analysis methods such as the QRAM are very useful during the conceptual design stage of a tunnel (Molag and Trijssenaar-Buhre, 2006). During this stage more accurate comparison among different tunnel design alternatives is possible and decisions have to be made on aspects such as the location and the length of the tunnel, the tunnel type (bored, cut and cover, immersed), the number and dimensions of the tubes, the type of traffic that can be allowed to use the tunnel. All the aforementioned decisions, which are made in the early design stage of a tunnel, will affect the overall safety during its entire life cycle. Safety considerations must always be part of the initial stage of conceptual development since 70 to 90 percent of the design decisions that affect safety will be made in these early project phases (Leveson, 2003). It must be clear that early integration of safety considerations into the tunnel design process allows maximum safety, therefore quantitative risk analysis methods should be implemented in this phase in order to make the right decisions as far as safety is concerned. It is much more expensive trying to mitigate the risk by adding protective equipment in tunnels which were unsafe from the beginning of their conceptual design stage.

3 RISK ANALYSIS FOR C&C TUNNELS

3.1 *Research question*

The aim of this work is to explore whether dividing a long cut and cover tunnel into shorter tunnel sections at the design phase would lead to higher or lower overall safety, assuming that dangerous good are allowed in the tunnel. The necessary hypothesis in this work is that it is technically possible to make such a decision. It must be highlighted that the only criterion examined was the overall safety of the two alternatives. The examination of financial factors was out of the scope of this work. It was initially expected that the open area dividing the tunnel sections would on one hand relieve the impact of a DGs accident inside the tunnel but on the other hand would share this impact to the surrounding environment. Especially for urban tunnels, where the surrounding environment of the tunnel consists of other roads, buildings and thus high concentration of population, the research question is of great importance. In order to find out whether the 'cutting' of a tunnel into a number of shorter segments in the design phase influences the overall tunnel safety, QRAM appeared to be a very useful tool.

Obviously neither all the road tunnels nor their surrounding environment are the same. For every single case, risk analysis is necessary when decisions of constructions' characteristics are made. This paper focuses in answering whether the division of a road tunnel section into shorter ones has an outstanding impact on tunnel safety.

3.2 *Research case description*

In order to explore the research question QRAM was selected as the probabilistic risk analysis tool to facilitate decision making. The model was applied for a case study tunnel, to come up with tangible results. The overall safety of the long tunnel compared to the overall safety of the shorter segments is examined by comparing the safety of the two alternative designs (from now on called routes). The first (route L) is one 3000m twin bore road tunnel. The second (route S) consists of three shorter twin bore road tunnels each of length 900m. In route S there are open road sections between the tunnel sections, with length 150 meters, as shown in figure 1.

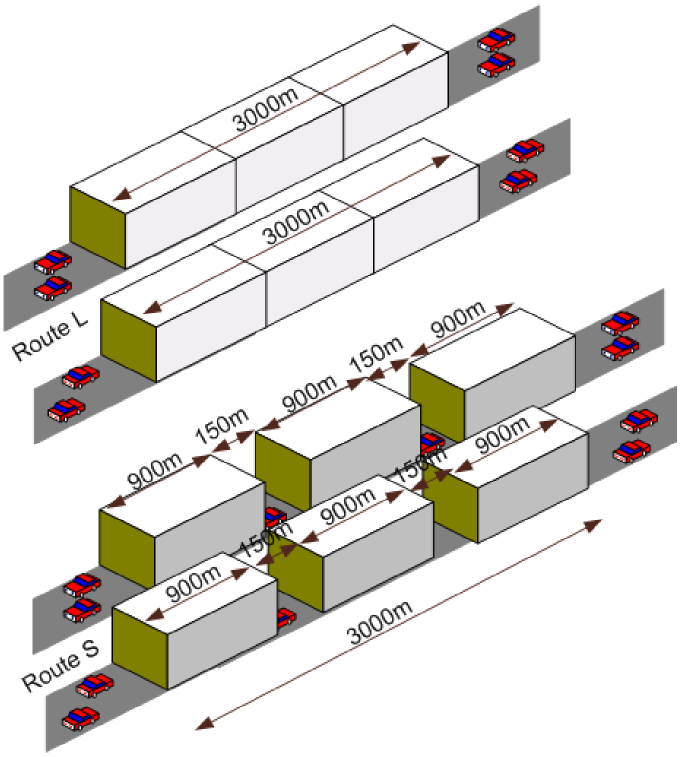

Figure 1. The two alternatives routes.

The length of the open area was chosen as short as possible so that the two alternative routes do not differ significantly in the total length of tunnel (3000m vs 2700m in the case examined). In both routes the construction is twin bore cut and cover. In order to conclude if there is a difference in the overall safety of the two alternatives, the safety level of the two routes was compared for three different cases. In **case 1** the average daily traffic is considered 10,000 vehicles per day. The surrounding population is assumed to be 2,000 inhabitants per square kilometer. The examination of the two different approaches is hereafter named, **case 1L** for the 3km tunnel (route L) and **case 1S** for the alternative option of the three shorter road tunnels (route S) for the aforementioned traffic and surrounding population data.

Considering that road tunnels are dynamic systems, meaning that some of their components are changing during time, in **case 2** the overall safety of the examined alternative routes was explored for a higher traffic volume, without changing any other of the parameters. The rationale behind this choice is that even if the overall safety of the two alternative examined routes does not differ significantly in the current traffic volume of 10,000 vehicles per day (case 1), future changes in traffic density should be taken into consideration, since traffic tends to be increased during a road tunnel's lifetime in most cases. This case aims at revealing if traffic volume is a critical parameter affecting the research question. In this case, **case 2L** stands for the 3km tunnel with traffic volume of 20,000 vehicles per day, whereas **case 2S** is the alternative option of the three shorter road tunnels with the traffic volume of 20,000 vehicles per day.

Finally, since one of the key questions was whether the three shorter tunnel sections would share the accident's impact to the surrounding environment more intensively than in the case of the single tunnel, the overall safety of the alternative routes for a denser surrounding population than the previous cases was examined in **case 3**. **Case 3L** is the 3km tunnel with surrounding population of 5,000 inhabitants per square kilometer and traffic volume of 10,000 vehicles per day, whereas **case 3S** is the alternative option of the three shorter road tunnels with the aforementioned traffic and surrounding population data.

It must be mentioned that the total traffic for all three cases is the traffic volume of both directions, as all the examined tunnels are twin bore. In a nutshell, the necessary data for using the QRA model for the three cases is presented in table 1.

Table 1. Cases' description

Case	Traffic volume (vehicles/day)	Surrounding population (people/square km)
1	10,000	2,000
2	20,000	2,000
3	10,000	5,000

In order to apply the QRAM some additional data were necessary. These data were considered to be the **same** for all the cases examined. As far as traffic data are concerned, the average speed is assumed to be 80km/h for the light vehicles and 60km/h for heavy good vehicles (HGVs) which is a typical average speed in urban tunnels. Other traffic related data that have been used are presented in Table 2.

Table 2. Traffic data

Traffic-related data	
HGV traffic (% of total traffic)	15
Bus traffic (% of total traffic)	1.5
Average number of persons in a car	1.85
Average number of persons in a HGV	1.17
Average number of persons in a bus	40

Another critical factor was the safety equipment of the tunnels. The tunnel in route L (cases 1L, 2L, 3L) must have exactly the same kind of equipment with the shorter tunnels in route S (cases 1S, 2S, 3S). Otherwise any difference in the overall safety of the two alternatives routes would stem from the different safety measures of the tunnels and not from the different construction option. The main characteristics of the tunnels are presented in table 3. It must be mentioned that in route S all the three tunnels have identical characteristics.

Table 3. Road tunnels characteristics

		Alternative routes	
		route L	route S
Construction data	Type	cut&cover	cut&cover
	Length(m)	3000	3 x 900
	Lanes (per direction)	2	2
	Gradient	0%	0%
	Camber	2.5%	2.5%
	Width(m)	9.32	9.32
	Open cross-sectional area(m^2)	64.3	64.3
Structural measures	Emergency exits	every 500m	every 500m
	Drainage open area (m^2)	0.009	0.009
	Dranage interval (m)	25	25
Ventilation (longitudinal)	Normal operation (m^3/s)	only piston effect	only piston effect
	Emergency Operation (m^3/s)	196	196
Mitigation measures		Siren/bell	Siren/bell

3.3 Research results

The following charts show the results of the QRAM for the three examined cases. In each chart the F/N curve of route L is compared to the F/N curve of route S for all the cases examined.

For case 1, case 1L results in an expected value (fatalities + injuries per year) of 3.554E^{-1}, whereas for case 1S the respective value is 3.282 E^{-1}. By this yardstick the level of safety in case 1L is slightly lower than in case 1S. As shown in Figure 2, the F/N curve of case 1L is slightly higher (lower safety) than the F/N curve of case 1S.

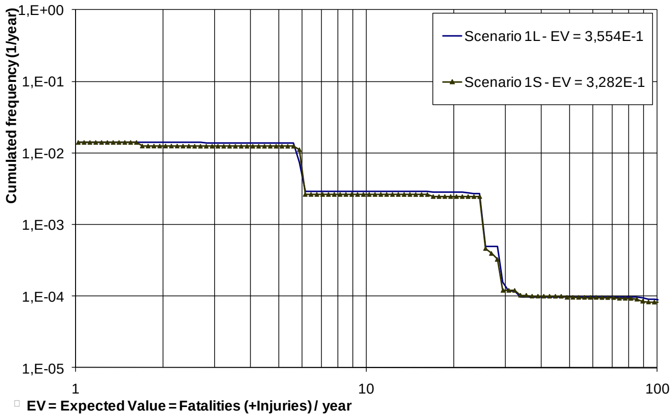

Figure 2. F/N curves for cases 1L and 1S

Table 4 presents the difference in the expected value for all the QRAM scenarios for DGs.

Table 4. QRAM results for case 1.

QRAM scenarios	Case 1L	Case 1S
All scenarios	$3.554E^{-1}$	$3.282E^{-1}$
20-100MW	$1.181E^{-1}$	$1.099E^{-1}$
Flammable liquids	$1.143E^{-2}$	$1.010E^{-2}$
Toxic products	$2.245E^{-1}$	$2.071E^{-1}$
Propane in bulk	$1.373E^{-3}$	$1.079E^{-3}$

For case 2 and specifically for case 2L the expected value (fatalities + injuries per year) is $8.340E^{-1}$ whereas for case 2S it is $7.693E^{-1}$. By this yardstick the level of safety in case 2L is slightly lower than that of case 2S. As presented in Figure 3, the F/N curve of case 2L is slightly higher (lower safety) than the F/N curve of case 2S.

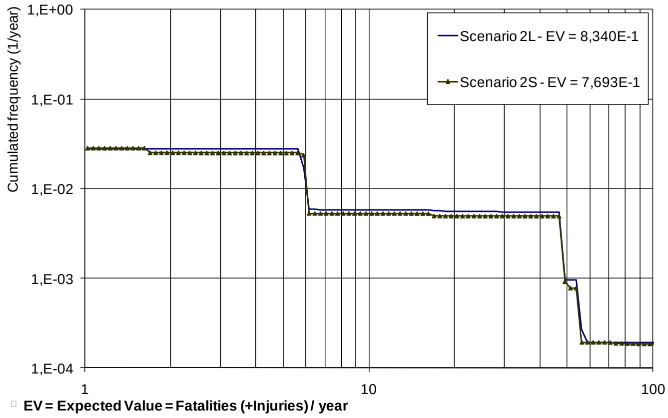

Figure 3. F/N curves for cases 2L and 2S

Table 5 presents the difference in the expected value for all the QRAM scenarios for DGs.

Table 5. QRAM results for case 2

QRAM scenarios	Case 2L	Case 2S
All scenarios	$8.340E^{-1}$	$7.693E^{-1}$
20-100MW	$3.359E^{-1}$	$3.094E^{-1}$
Flammable liquids	$4.275E^{-2}$	$3.833E^{-2}$
Toxic products	$4.501E^{-1}$	$4.179E^{-1}$
Propane in bulk	$5.269E^{-3}$	$3.636E^{-3}$

Finally, for case 3 and for case 3L the expected value (fatalities + injuries per year) is $6.646E^{-1}$ whereas for case 3S it is $6.109E^{-1}$. By this criterion the level of safety in case 3L is slightly lower than that of case 3S since, as shown in Figure 4, the F/N curve of case 3L is slightly higher (lower safety) than the F/N curve of case 3S.

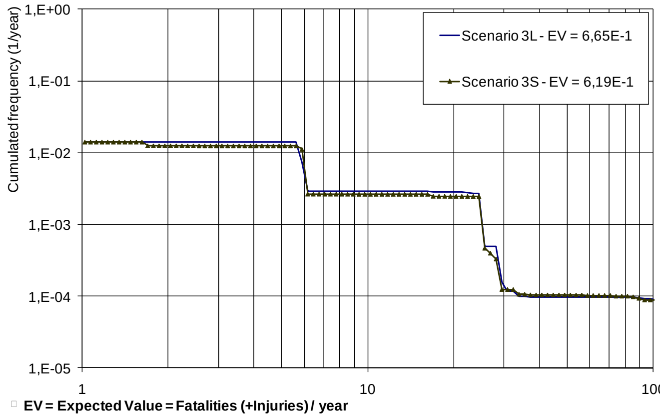

Figure 4. F/N curves for cases 3L and 3S

Table 6 presents the difference in the expected value for all the QRAM scenarios.

Table 6. QRAM results for case 3.

QRAM scenarios	Case 3L	Case 3S
All scenarios	$6.646 E^{-1}$	$6.109 E^{-1}$
20-100MW	$1.181 E^{-1}$	$1.099 E^{-1}$
Flammable liquids	$1.143 E^{-2}$	$1.012 E^{-2}$
Toxic products	$5.336 E^{-1}$	$4.978 E^{-1}$
Propane in bulk	$1.460 E^{-3}$	$1.187 E^{-3}$

The increase in the traffic volume that differentiates case 2 from case 1 or the denser surrounding population of case 3 compared to case 1 naturally increase the expected value of fatalities and injuries. However, in all the aforementioned cases, the safety of route L is slightly lower than in route S.

4 CONCLUSIONS

The aim of this work was to explore a particular case where dangerous goods have to pass through typical cut and cover road tunnels. The question explored was whether dividing a long tunnel into three shorter sections at the conceptual design stage would affect the overall safety. Early decisions in the geometrical characteristics of a tunnel would affect its overall safety during its whole life cycle and therefore the research question is of outmost importance in the early stages of such a construction project. In order to conclude, quantitative risk analysis tools and specifically the OECD /PIARC QRA Model was used to perform the risk analysis of the cases examined. The overall safety of the first alternative (one long tunnel - route L) was compared to the other alternative of its division into three shorter tunnels (route S) for three different cases.

According to the calculations of the model, ‘cutting’ the tunnel into three shorter sections leads always to a safer state. However, the difference in the Expected Value of the risk as well as the comparison of the F/N curves for all the cases examined is not big enough to indicate a doubtless superiority of the shorter sections (route S) against one long tunnel (route L). According to PIARC (2008) when the ratio of the EV of two alternative routes is less than 3 (which is valid for all the cases examined here) then other criteria are required to make a decision on which one is safer.

Thus, other factors such as the psychological condition of road tunnel users in the two possible alternatives should be taken into account. One could claim that the alternative of the shorter tunnels (route S) would reduce the sense of claustrophobia among tunnel users and, since tunnel users' behavior is a critical factor in road tunnels safety, route S would be a safer option than route L. On the other hand, route L could be considered much safer than route S in cases of unfavourable meteorological conditions. For example, consecutive small tunnels are less safe in case of frost, heavy rain or glaring from sunlight.

As a conclusion, the answer to the research question as far as the transportation of dangerous goods is concerned is that there is no evidence of increase in safety from dividing a long urban cut and cover tunnel in smaller parts with open air areas in between. However, the overall safety (that should take into account all risks and not only those that are due to the transportation of dangerous goods) depends to a great extend on the specific characteristics of each particular case, since there are many factors that influence the overall safety of road tunnels. These factors are not taken into consideration by any quantitative risk analysis model, and also by the QRAM. The QRAM only considers increased probabilities of accidents near tunnel portals, a factor that influences risk in route S of the cases examined but does not consider many other critical factors. Therefore it is concluded that risk analysis using systemic approach is crucial for any road tunnel as early as in the design phase and lasting for its whole lifecycle. Moreover, quantitative risk analysis models such as the QRAM should not be the sole basis for decision making by tunnel operators or Administrative Authorities. As Apostolakis (2004) states safety-related decision making is risk-informed, not risk-based. Thus, as far as road tunnel safety is concerned, a systemic approach combining quantitative risk analysis tools with traditional safety analysis and systems theory principles should be implemented.

5 REFERENCES

Apostolakis, G. 2004. How useful is Quantitative Risk Assessement?, *Risk Analysis* 24(3): 515-520.

COVO Report. 1982. *Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, A Pilot Study*, Reidel Publ. Co, Dordrecht .

EC, 2004. Directive on minimum safety requirements for tunnels in the trans-European road network, *Official Journal of the European Union*, L 167 (30.4.2004).

INERIS. 2005. *Transport of Dangerous goods through road tunnels Quantitative Risk Assessment Model (v. 3.60 and v. 3.61) Reference Manual*, Verneuil-en-Halatte, France.

Khoury, G.A and Molag, M. 2005. Actual time tunnel safety-A new approach, *Tunnels and Tunelling International* 37(7), 46-48.

Knoflacher H., Pfaffenbichler P.C. and Nussbaumer H. 2002. *Quantitative Risk Assessment of Heavy Goods Vehicle Transport through Tunnels - the Tauerntunnel Case Study*, 1st International Conference Tunnel Safety and Ventilation, Graz.

Leopoulos, V., Kirytopoulos, K., and Malandrakis, C. 2006. Risk management for SMEs: Tools to use and how, *Production Planning and Control* 17(3): 322-332.

Leveson N. 2003. *White Paper on Approaches to Safety Engineering*, in Sofeware, Addison-Wesley (ed.), Sofeware, Boston.

Molag, M. and Trijssenaar-Buhre, I. 2006. Risk Assessment Guidelines for Tunnels, *Safe & Reliable Tunnels Second International Symposium*, Lausanne.

OECD. 2001. *Safety in tunnels – Transport of dangerous goods through road tunnels*, Organization for Economic Co-operation and Development - OECD Publications, Paris.

PIARC. 2008. *Risk analysis for road tunnels*, World Road Association (PIARC), France.

Rasmussen, NC. 1975. Reactor Safety Study, Nuclear Regulatory Commission Document WASH-1400, NUREG 75/014.

Rentizelas, A., Tziralis, G., Kirytopoulos, K. 2007. Incorporating uncertainty in optimal investment decisions, World Review of Entrepreneurship, *Management and Sustainable Development* 3(3-4): 273-283.

SAFE-T. 2008. *Appendix 1: Tools for Probabilistic risk assessment*, SAFE-T research project report.

Tziralis, G., Kirytopoulos, K., Rentizelas, A. and Tatsiopoulos, I. 2009. Holistic investment assessment: Optimization, risk appraisal and decision making, *Managerial and Decision Economics* 30(6): 393-403.