Quantitative risk analysis on the transport of dangerous goods through a bi-directional road tunnel

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Abstract

A quantitative risk analysis (QRA) regarding dangerous goods vehicles (DGVs) running through road tunnels was set up. Peak hourly traffic volumes (VHP), percentage of heavy goods vehicles (HGVs), and failure of emergency ventilation system were investigated in order to assess their impact on the risk level. The risk associated with an alternative route running completely in the open air and passing through a highly populated urban area was also evaluated. The results in terms of social risk, as *F/N* curves, show an increased risk level with an increase the VHP, the percentage of HGVs, and a failure of emergency ventilation system. The risk curves of the tunnel investigated were found to lie both above and below those of the alternative route running in the open air depending on the type of dangerous goods transported. In particular, risk was found to be greater in the tunnel for two fire scenarios (no explosion). In contrast, the risk level for the exposed population was found to be greater for the alternative route in three possible accident scenarios associated with explosions and toxic releases. Therefore one should be wary before stating that for the transport of dangerous products an itinerary running completely in the open air might be used if the latter passes through a populated area. The quantitative risk analysis may help decision-makers both to implement additional safety measures and to understand whether to allow, forbid or limit circulation of DGVs.

Keywords:

Quantitative risk analysis, road tunnels, dangerous goods vehicles, peak traffic volume, alternative route.

1. Introduction

Risk analysis is an important tool which can be useful for improving and/or optimizing the safety level of road tunnels. Although the frequency of significant tunnel accidents is low, the consequences expected can be very severe in terms of: (i) fatalities and injuries; (ii) damage to vehicles and tunnel structures (e.g., concrete spalling, ceiling collapsing, pavement burning); (iii) destruction of equipment (e.g., ventilation, lighting, road signs, and monitoring systems); (iv) disturbance to the traffic flow and impact on its distribution along alternative roads due to the partial or total closure of tunnel; (v) effect on transport economy (e.g. direct costs of tunnel rehabilitation, economic losses related to vehicles and goods, indirect costs of the extra transport time caused by the reduced service level of a tunnel or its temporary closure).

Risk analysis methods were initially developed to assess the safety of potentially dangerous plants and processes in the nuclear, chemical and petrochemical sectors. The methods have been subsequently adapted and applied to road tunnels. In this respect, the European Parliament and Council adopted the European Directive 2004/54/EC(1) that is applicable to all tunnels in the Trans-European Road Network with lengths over 500 m. In this Directive, when a tunnel is opened to dangerous goods, it is explicitly required 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**.** The Italian Ministry of Infrastructure and Transports(2) has adopted the aforementioned Directive, with the date of its coming into force in Italy being the 24th of October 2006. In this respect, the Italian Management Agency of National Roads and Motorways (ANAS) subsequently published certain guidelines(3) for the design of safety in Italian road tunnels.

There are several methods for evaluating the safety level of tunnels and the effectiveness of safety measures that can be implemented for reducing the consequences of accidents. However, the quantitative risk analysis (QRA) is generally used, which differs from the qualitative risk analysis on account of its including a lower uncertainty level. Two main kinds of approaches appertain to QRA, which are deterministic and probabilistic, respectively. The deterministic method can give accurate results if the exact input parameters are known, and is also useful for determining trends due to its single parameter variation. The probabilistic method, instead, is generally considered to be the best tool for taking into account the uncertainty associated with some parameters describing the process and for assessing long-term risk in more complex systems (e.g. tunnels). A probabilistic method involves the identification of hazards, the estimations of probability and consequences of each hazard, and quantifies the risk as the sum of probabilities multiplied by consequences. According to this approach, QRA includes event trees, faults trees and consequences estimation models. Individual risk (e.g. the probability of death per year for a specific person exposed to a risk), societal risk (e.g., the expected number of fatalities in the tunnel per year) and estimates of damages (structural and environmental) are considered output of QRA. In this respect, the societal risk is often used. Frequently, it is represented in the form of an *F/N* curve, where *F* is the cumulative probability that the number of fatalities is equal to or greater than a given number *N*. The *F/N* curve that is found for each scenario is then needed to be compared with threshold values of tolerable and intolerable risk. Moreover, between these two risk thresholds an area of conditional tolerable risk, which is the so-called ALARP (As Low as Reasonably Praticable), is often also defined.

The PIARC (The Permanent International Association of Road Congress)[(4)] reports a summary of the worldwide application of risk methodologies for road tunnels and provides details about the methods adopted and the experience of practical applications in several countries. In this regard among different risk methods is to be quoted, for example, the Austrian model, which is known as TuRisMo, the Dutch TUNPRIM model, the Italian Risk Analysis Method (IRAM), and the French Specific Hazard Investigations. However, it is to be stressed that in many European countries (e.g. Austria, Switzerland, France, and Greece) the QRAM (Quantitative Risk Assessment Model) is the one most widely used for making decisions on the transport of dangerous goods (DG). In Italy, instead, the risk assessment for dangerous goods is included in a general approach, while the DG-QRAM has only recently begun to be used so that few Italian studies are available. Thus, as a result, this paper gives consideration to the application of the aforementioned DG-QRAM to Italian conditions.

The circulation of hazardous materials on roads is generally governed by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), adopted in 1957 under the auspices of the United Nations Economic Commission for Europe, which has recently been upgraded by taking new amendments into account(5). This document also contains some general recommendations for the passage of vehicles carrying dangerous goods through road tunnels. However, the question regarding the circulation of hazardous materials in tunnels, given that these are closed structures except at the entrance and exit portals, appears to be more complex compared to that on open roads, and it is clear that any approach to this problem needs to be well investigated by a specific risk analysis. On the other hand, it is to be said that also the common freight vehicles and/or passenger vehicles, which often have a frequency of circulation on roads much greater than that of vehicles carrying dangerous goods, can have the potential of causing significant accidents in tunnels. In fact, in tunnels we can have high temperature levels, relevant concentrations of toxic gases, and poor visibility for people evacuation also in the event of a fire source with a peak of the heat release rate (HRR) that presents an average value. In other words different vehicle types with their own circulation frequency and loads, other than those classified as carrying dangerous goods, can also prove very dangerous. Nevertheless, it is to be said that only few studies available in the literature on risk analysis have investigated both different vehicle types and their circulation frequency through road tunnels. Therefore it is shown that this subject should be better examined, which is also one of the purposes of this paper.

The effects of a fire source in a tunnel, however, also depend on vehicle traffic intensity. When this is high, the tunnel might be almost full of vehicles at the time of a serious accident and the presence of these vehicles, which act as obstacles, may influence the temperatures and spreading of smoke, as well as the performance of the ventilation system. Moreover, the fire spreading from the initially burning vehicle might also involve other vehicles. On the contrary when traffic intensity is low, less severe consequences might be expected. Most risk analyses are based on traffic flow expressed only in terms of the annual average daily traffic (AADT). Indeed traffic flow is not constant but can vary seasonally (e.g., a road serving a sea-side city or a beach resort area may be little used during much of the year but becomes oversaturated during the peak summer periods), and during the day (e.g. peak traffic volumes are expected more especially in the mornings and/or evenings compared to night ones). Therefore in some cases making a risk analysis of tunnel based only on the AADT might be not justified. Taking into account that traffic flow can vary seasonally and/or during the day can help us in getting a better understanding whether the circulation through the tunnel of vehicles carrying dangerous goods or ordinary loads should be free, forbidden, limited to specific products, or permitted during specific time periods, all of which also falls within the scope of this paper.

The consequences of a serious accident in tunnels also depends on vehicle speed. When the speed is higher than the imposed speed limit at the tunnel entrance the effects of hitting something (e.g. other vehicles or tunnel walls) might be very serious with a greater probability of causing fire sources. On the other hand the number of occurrences of electrical and/or mechanical defects of vehicles, which are known to be mostly responsible for fires in tunnels, might be expected to increase with increased vehicle speed. Therefore, the imposition of a low speed limit before entering the tunnel might prove appropriate. Moreover this also may bring that the spatial distance from vehicles, travelling inside the tunnel at the imposed speed limit in the same direction along a lane of carriageway, might be sufficient enough for ensuring safer braking distances against rear-end collisions. However, a low speed limit also means that the vehicles would remain for a longer time within the tunnel, which might increase exposure to accident risk. In this respect the literature on this subject appears to be rather scarce. Therefore it is clear that the speed of tunnel users travelling above the imposed speed limit should be better investigated by means of a quantitative risk analysis. In this respect, however, it is to be said that one of the limitations of the DG-QRAM is that it appears to be unable to show how the risk level changes when the speed of vehicles increases.

Although forbidding the circulation of dangerous goods through tunnels would improve the safety of tunnel users, it would nevertheless, at the same time, expose people living close to alternative routes to additional risks. In fact, alternative routes might cross urban sites where the consequences of a serious accident may affect a greater number of people compared to those in the tunnel. In addition, alternative routes might be much longer than the direct route including the tunnel investigated, which may increase the exposure of these vehicles to accidents. Therefore, risk analysis should be associated with both the tunnel and alternative routes running in the open air when the transport of hazardous materials is investigated, which is another intent of this work.

In the light of the aforementioned considerations, there are three reasons for justifying this paper. The first, since the traffic flow may vary seasonally and/or during the day, is to single out specific time periods during which the circulation of vehicles carrying dangerous goods may be allowed through the tunnel under safer conditions. The second is to compare the results of quantitative risk analysis in tunnels to those obtainable by considering alternative routes running completely in the open air. A third reason is to refresh the lessons learned from the application of the widely-used DG-QRAM.

In this paper, the tool used is based on quantitative risk analysis. In particular the so-called DG-QRAM (Dangerous Goods-Quantitative Risk Assessment Model) that was proposed jointly by PIARC and OECD (Organization for Economic Co-operation and Development) with associated software developed by INERIS[6] was used. In order to achieve the purpose of this work, a specific tunnel is investigated. This tunnel, labelled Varano, is located in the South of Italy along a rural road (S.S. 145) serving the sea-side city of Sorrento which is known to be a tourist locality with its numerous bathing resorts. Therefore this tunnel is affected by very high traffic flow more especially in the summer periods, but is less used during the rest of the year. As far as the authors are aware, the circulation of vehicles carrying dangerous goods in the aforementioned tunnel is not forbidden at the time of the writing of this paper. The tunnel, which is a curved bi-directional road tunnel, is 1.2 km long. This structure presents a positive longitudinal slope from Portal A to B (+ 2% in an ascending direction towards Sorrento). The tunnel investigated is currently being improved in compliance with the European Directive 2004/54/EC, with a longitudinal ventilation system that will be able to provide efficient forced airflow in the ascending direction. The ventilation system will be constituted by eight pairs of axial jet fans fixed on the tunnel ceiling. In ordinary traffic conditions the first pairs of fans are activated for providing a minimum level of ventilation (air average velocity of 2-2.5 m/s), while in the event of a fire emergency the activation of all fans supply an air flow at the velocity of 9 m/s in order to remove and control smoke and toxic gases generated by fire. A linear heat detection system is assumed to activate the emergency ventilation system when the temperature is above 68 °C. With reference to the mentioned tunnel, it is to be said that in Caliendo et al.[7] the effects of a fire source due to a heavy goods vehicle (HGV) with a peak of the heat release rate (HRR) of 50 MW is investigated by using a computational fluid dynamic (CFD) modelling; in Caliendo et al.[8] the findings obtained by means of a simulation model for representing an evacuation process of people from the aforementioned tunnel in the event of a fire is also described; finally in Caliendo et al.[9] the results are shown as obtained by CFD modelling for simulating the effects of fire, with and without traffic, due to four different vehicles with HRR peaks of 8, 30, 50 and 100 MW, representing two cars, a bus, a heavy goods vehicle, and a petrol tanker, respectively. However it is to be stressed that in these papers, studies based on the quantitative risk analysis were not carried out.

Such, then, is the context wherein the present work is set. The paper sets out to make an additional contribution to our knowledge by helping us to understand more about the main questions specified earlier (frequency of circulation of different vehicle types through road tunnels, seasonal traffic variability and/or during day) by means of quantitative risk analysis applied both to the aforementioned tunnel and to the alternative route.

In the light of the above considerations, the present paper is organized as follows: the next section contains a literature review concerning risk analysis in tunnels, whereas the subsequent section deals with the reference scenarios for quantitative risk analysis. The results of computer simulations are then presented and discussed, and an evaluation of safety is made. Finally, the conclusions and directions of future research are reported.

2. Literature review

As far as the authors are aware the first quantitative definition of risk is generally attributed to Kaplan and Garrick[10]. These authors argued that a risk analysis consists of a response to three main questions: “what can happen? (i.e. what can go wrong?)”; “how likely is it that will happen?” and “if it does happen, what are the consequences?”. A response to three such questions was expressed as a triplet $<S_i, p_i, x_i>$ where, S_i is a scenario, p_i is the probability of that scenario, and x_i is the consequence of the scenario (i.e. the measure of damage), respectively. After this pioneering work, several studies were developed on quantitative risk analysis. However in this paper only those concerning road tunnels are of interest.

In keeping with the studies made in the last few years, Saccomanno and Haastrup[11] described the DG-QRAM developed in Europe that can be used to estimate the risk of transporting dangerous goods through road tunnels and to assess the effectiveness of risk reduction measures for some typical scenarios. In this respect, the authors introduced in their paper a procedure for extending the scope of the QRA model in order to include safety measures that were not part of the original model. Their procedure used expert judgements and Monte Carlo simulation methods to model uncertainty in the revised risk estimates.

Knoflacher and Plaffenbichler[12] carried out a Quantitative Risk Analysis (QRA) for 13 selected Austrian tunnels. Their study covered uni- and bi-directional tunnels and a wide range of different tunnel lengths (1-10 km), AADT, percentage of trucks, and ventilation systems. The software used, which is the aforementioned DG-QRAM, is based on the use of social risk expressed in the form of F/N curves. Threshold values of tolerable and intolerable risk are presented. These authors found that the F/N curves of all investigated tunnels did not reach the intolerable risk threshold (i.e. additional safety measures were not required). However, the authors suggested enforcing HGV-drivers to maintain low speeds and/or a minimum 150-metre distance from vehicles ahead.

Hall et al.[13] claimed that the QRAM can be used to quantify risks and help to answer key questions for the management of dangerous goods traffic in tunnels and on open roads. Examples of application were presented to show how this software has been used in some European countries.

Parson Brincherhoff Quade & Douglas[14] investigated both the Eisenhower/Johnson Memorial Tunnels (EJMT) and alternative roads by using the aforementioned QRAM model. They verified that it is appropriate to maintain the current procedure based on the circulation of hazardous material trucks over alternative roads, since the risk of dangerous goods transport through the EJMT would be too great in terms of potential for a catastrophic loss of life, infrastructural damage and environmental impact.

Holicky[15] considered three different types of risk criteria (individual, expected, and social) for road tunnels. Recommendations for the lower and upper limits of relevant risk indicators are derived from commonly accepted safety requirements.

By investigating the risk associated with the road transport of hazardous materials through tunnels, Bubbico et al.[16] found a higher risk in tunnels when compared to that on open roads. However, their results recommended that the circulation in road tunnels of some types of dangerous goods should be allowed or forbidden on the basis of a specific risk analysis.

Petelin et al.[17] also used the aforementioned QRAM and presented a risk acceptability criteria for Slovenia. More especially a case study based on the investigation of a tunnel constituted by two tubes, one of which with unidirectional traffic, was investigated. Increased risk was found when one tube was closed for rehabilitation and the other one was temporarily affected by bidirectional traffic. Therefore, the authors suggested the use of an alternative open road whereby less risk was obtained by forming a by-pass for the tube section closed for rehabilitation (leaving the other tube open for unidirectional traffic).

Kyritopouolos et al.[18] examined whether the minimum safety measures imposed by Directive 2004/54/EC (when heavy goods vehicles (HGVs) and dangerous goods vehicles (DGVs) are allowed through tunnels) were sufficient to lead to acceptable social risk levels, as defined by the limits of ALARP models, when evaluated by the QRAM. Five case studies were investigated, each case representing one of the tunnel classes of the aforementioned Directive in terms of traffic and length of tunnels. The results showed that in cases of longer tunnels (≥ 3000 m) and affected by high traffic volumes (≈ 5000 vehicles/lane) the risk exposure (F/N curves) lies beyond the acceptable safety limits of ALARP models. Therefore, in these cases more safety measures and/or the risk associated with alternative roads should be taken into account.

Diernhofer et al.[19] used the DG-QRAM to assess the risk involved in transporting dangerous goods through tunnels or open roads, as well as the Austrian Tunnel Risk Model (TuRisMo) for assessing the risk related more especially to mechanical accidents and/or fire scenarios. They developed a simplified risk assessment process in keeping with ADR tunnel regulations and acceptance criteria for each level of investigation.

Steiger et al.[20] also used TuRisMo and QRAM which, in contrast with the TuRisMo, differentiates between various types of dangerous goods. They found that a local smoke extraction system for a twin-tube tunnel, can be replaced by a portal-to-portal longitudinal ventilation system with reduced distances between emergency exits.

Meng et al. [21] investigated traffic volume and percentage of heavy goods vehicles (HGVs) that can significantly affect social risk. The authors showed that these parameters can be very useful in implementing risk reduction solutions. The methodology proposed, which uses the QRAFT model based on social risk criteria, was applied to a Singapore road tunnel showing that the maximum tolerable traffic volume and percentage of HGVs in the case investigated was 1200 veh/hour per lane and 18%, respectively.

Nývlt et al.[22] introduced an adjusted probabilistic risk assessment into the risk analysis framework and enabled its being incorporated into the risk management process. According to these authors their proposed analysis provides support material for decision-makers and risk-managers. In this respect, the results of a case study of the Strahov tunnel in Prague were presented.

Zulauf[23] discussed some specific aspects of risk strategies and provided recommendations for the practical use of risk evaluation criteria. In particular, it is stressed that risk evaluation may be closely dependent on the method of risk analysis chosen, and that the results of quantitative risk analysis should be considered accurately and supported by sensitivity studies.

Ronchi et al.(24) proposed a review of the Italian Risk Analysis Method (IRAM) in terms of its applicability for people evacuation from tunnels. These authors provided suggestions for improving and upgrading the Italian approach to evacuation modelling tools.

By investigating the freeway tunnel accidents in China, Zhou et al.(25) proposed a risk-assessment approach based on a multiple safety index which is weighted by taking into account the knowledge of experts and the implied information on data.

The above chronological presentation of the literature shows that studies are focused more especially on certain factors that may influence the risk level in road tunnels. A wider assessment that contemporaneously compares different vehicle types and their frequency, season and/or daily traffic variability, and alternative roads, does not appear, in contrast, to have been sufficiently well made. Thus this paper focuses on these factors all at the same time.

3. Reference scenarios

Available traffic data were expressed in terms of annual average daily traffic (AADT). The AADT is given as 20,000 vehicles/day for the bidirectional flow (i.e. 10,000 vehicles/day per lane), with a percentage of heavy vehicles equal to 5% (4% freight vehicles and 1% buses, respectively). On the basis of these data we first estimated an average peak hourly volume (VHP) of 2400 vehicles/hour. Given that the traffic could vary seasonally, we assumed a higher peak hourly volume (VHP) in summer (from June to August) equal to 3200 veh/h (1600 veh/h per lane); where VHP = 2100 veh/h (two-thirds of 3200 veh/h) was assumed to be the traffic travelling during a specific daytime peak hour in summer and 1100 veh/h (one-third of 3200 veh/h) for that of night time. The imposed speed limit is 50 km/h; and vehicles were forbidden to overtake.

A complete assessment of the quantitative risk analysis on the transport of dangerous goods through tunnels would include considering all kinds of dangerous materials and/or whether vehicles are fully or partially loaded, as well as the introduction of other variables of interest. Since all circumstances cannot be considered, simplifications have generally to be made. In this respect, we used the DG-QRAM software that considers 13 accident scenarios which are representative of key dangerous goods groupings. These scenarios are listed as follows: (1) heavy goods vehicle (HGV) with no dangerous goods (HRR = 20 MW); (2) heavy goods vehicle (HGV) with no dangerous goods (HRR = 100 MW); (3) boiling liquid expanding vapour explosion (BLEVE) of a 50 kg of propane cylinder; (4) motor spirit pool fire; (5) vapour cloud explosion (VCE) of motor spirit; (6) chlorine release from a 20-ton tank; (7) BLEVE of a 18-ton propane tank; (8) VCE from a 18-ton propane tank; (9) propane torch fire; (10) ammonia release from a 20-ton tank; (11) acrolein release from a 25-ton tank; (12) acrolein release from a 100-litre cylinder; (13) BLEVE of a 20-ton liquefied CO_2 (carbon dioxide) tank. With reference to the aforementioned scenarios, it is to be said that the scenarios 1 and 2 (HGVs that do not carry dangerous goods) are only considered for comparison reasons.

The DG-QRAM also takes into account: accident frequencies (derived from historical datasets); physical consequences of incidents; escape and sheltering effects; effects of hazards (such as heat and smoke) on people. A wide range of information is required in order to operate the DG-QRAM. In particular, for example, the following data have to be introduced, namely tunnel geometry, ventilation system, drainage, emergency escape measures, traffic characteristics (including vehicle mix and traffic speeds), and population along the route containing the tunnel studied. The results for different scenarios and traffic conditions are reported in terms of the so-called social risk. This relationship is illustrated for each scenario by an *F/N* curve. Each curve can also be evaluated in terms of a single value representing the average number of fatalities per year, called the expected value (EV).

In the light of the above considerations and assumptions, many cases were investigated, the results of which are subsequently summarized with reference both to the tunnel studied and open route running completely in the open air.

4. Analysis of results

4.1. Road tunnel

In this paragraph the results of the DG-QRAM applied to assessing the risk level associated with dangerous goods vehicles (DGVs) and heavy goods vehicles (HGVs) travelling through the tunnel investigated are presented. With reference to the summer period, where the range of peak hourly volume (VHP) is assumed to be equal to 1100, 2100, and 3200 veh./h, respectively, the most dangerous combinations of scenarios in terms of the social risk, as expressed by the F/N curve, are more especially commented on (each curve can be evaluated synthetically also by using the corresponding expected value EV). The aggregated scenarios representing the most relevant critical events were found to be: heavy goods vehicles (HGVs) with no dangerous goods (HRR = 20-100 MW); DGVs with flammable liquids; DGVs with toxic products, DGVs with propane in bulk, and BLEVE except bulk propane.

Figure 1 shows that the F/N curve for each of the aforementioned scenarios is below the Italian upper ALARP (as low as reasonably practicable) limit. In this regard it is to be specified that the threshold values for intolerable risk are between 10^{-1} and 10^{-3} respectively for N = 1 and N = 100 fatalities (if the F/N curve exceeds this limit, safety measures for risk reduction must be taken), whereas the threshold values for tolerable risk are between 10^{-4} and

10^{-6} respectively for N = 1 and N = 100 fatalities (if the F/N curve lies below this limit extra safety measures are not necessary). If the F/N curves are within the ALARP region according to the Italian Ministry of Infrastructure and Transport (2006) the possibility of implementing additional safety measures should be justified by a cost-benefit-analysis. Since our results show that the F/N curves are within the ALARP region and/or below the lower ALARP limit, supplementary measures for risk reduction would not be strictly necessary in the case investigated, unless a benefit-cost analysis, which is not within the scope of this paper, were able to prove the contrary.

However, it is to be noted that an increased risk (F/N curves close to the upper ALARP limit) was found for the HGVs (HRR = 20-100 MW) rather than for the DGVs. This might be attributed to the fact that HGVs travel with greater frequency through tunnel compared to DGVs (i.e. the proportion of HGVs in traffic flow is higher than that of DGVs), as a result a higher exposure to risk is expected. Additionally it is to be said that for a similar scenario, the risk level was found to increase with an increase in the VHP. In other words lower risk levels are expected when the VHP is low (e.g. at night). Therefore it is suggested that if the Tunnel Management Agency (TMA) wished to increase the safety level in the tunnel investigated in summer the circulation of dangerous goods vehicles (DGVs) might be permitted more especially by night (e.g. from 22:00 p.m. to 6:00 a.m.), as well as that of HGVs.

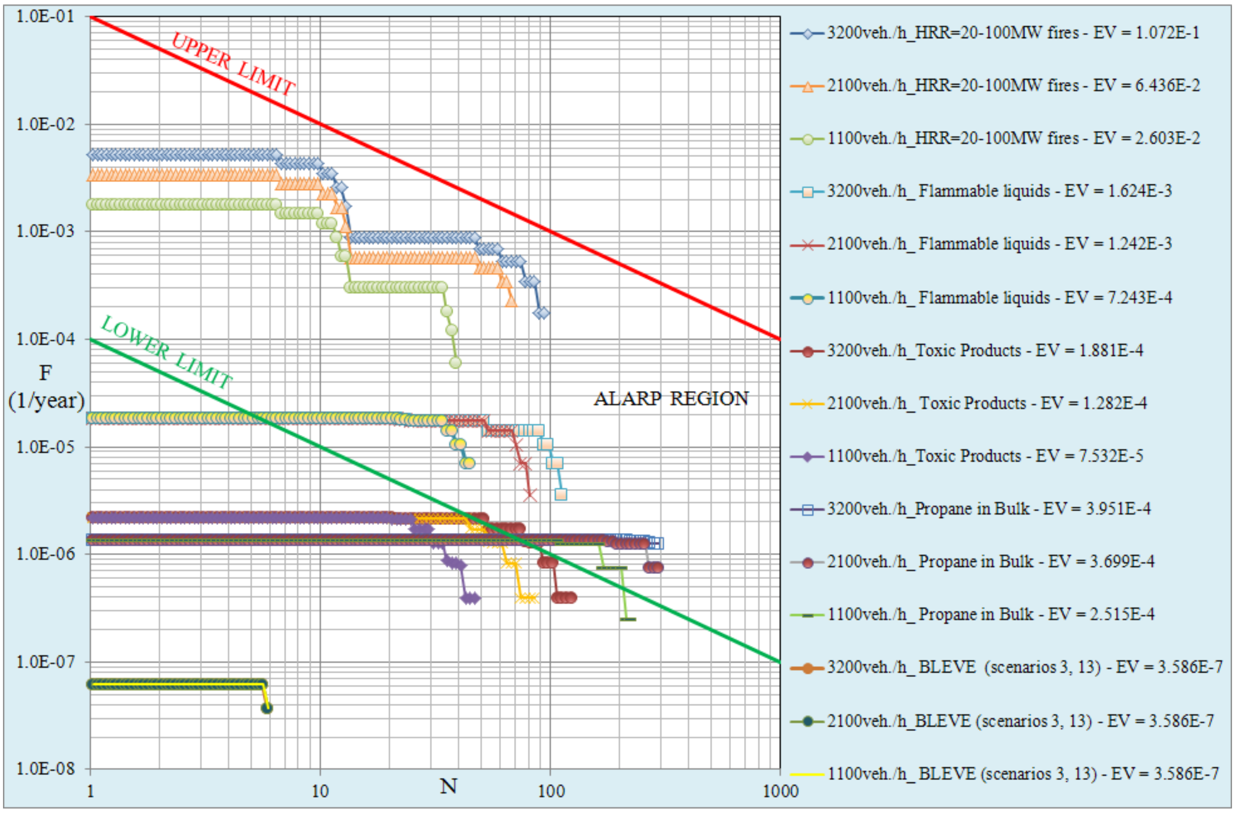

Fig.1. F/N curves for the most dangerous scenarios in different traffic conditions (VHP = 3200 veh./h, VHP = 2100 veh./h during the day, and VHP = 1100 veh./h during the night) and Italian ALARP limits.

Figure 2 shows the F/N curves of aggregated scenarios for DGVs (with flammable liquids, toxic products, propane in bulk, or BLEVE except bulk propane) for an increase in the percentage of heavy goods vehicles (HGVs) from 5 % to 10% in the traffic flow. The F/N curves, even if contained in the ALARP region, lie farther from the lower limit. This indicates that the tunnel will operate below a lower safety level if an increased percentage of heavy vehicles is expected in the traffic flow.

In this circumstance, if the TMA wished to maintain a lower risk level it might implement some operational procedures; for example it might enforce dangerous goods vehicles (DGVs) to pass through the tunnel at night (as it has been already written before). In fact when the VHP =1100 veh/h (at night) the risk level is lower than that associated with VHP = 2100 veh/h.

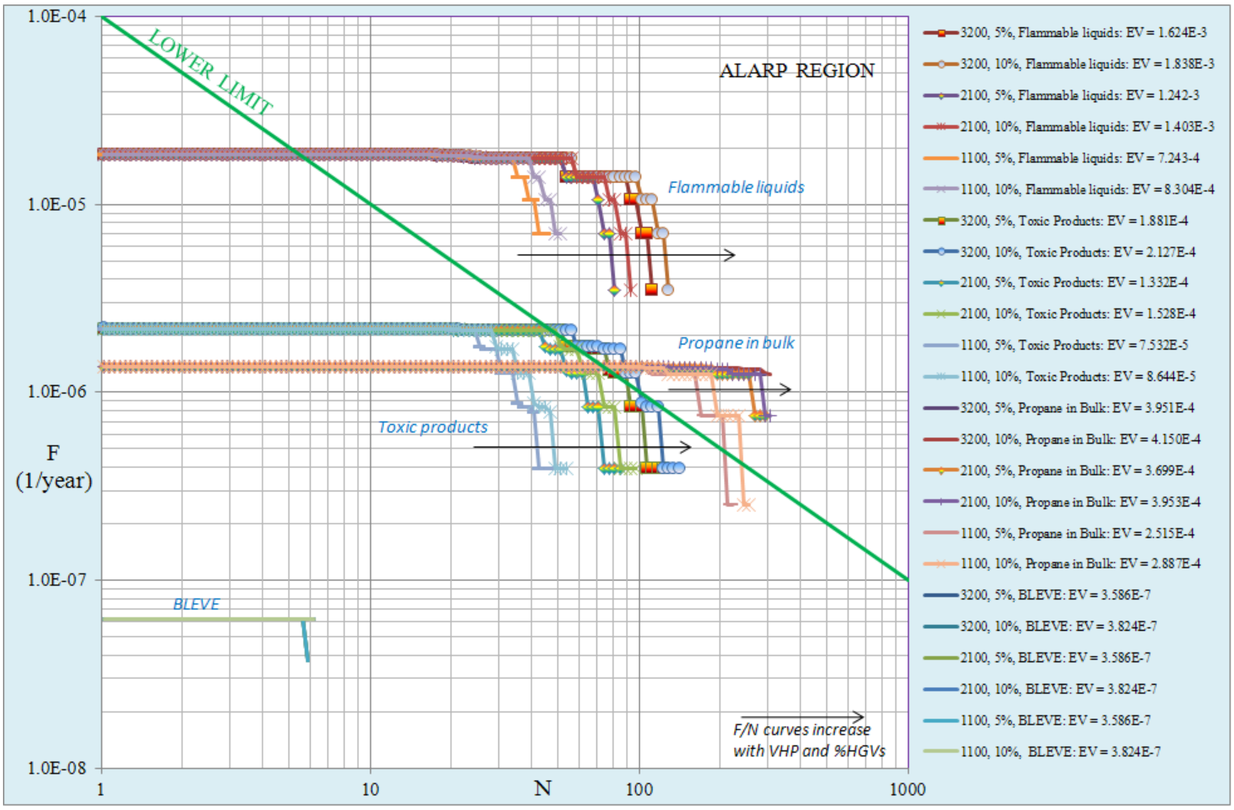

Fig.2. F/N curves for aggregated scenarios of DGVs and for an increase in the percentage of heavy goods vehicles in traffic flow (from 5% to 10%) in different traffic conditions (VHP = 3200 veh/h, VHP = 2100 veh./h during the day, and VHP = 1100 veh./h during the night).

Figure 3 shows what happens if the emergency ventilation system does not work in the case of a critical event. This figure proves that the F/N curves of aggregated scenarios for dangerous goods vehicles (DGVs) are within the ALARP region or do not exceed the lower limit. However, the F/N curve of scenario caused by DGVs with flammable liquids lies over the F/N curves associated to an explosion or release of toxic products. Maybe one possible explanation might be that the occurrence frequency of fire with flammable liquids is higher than that of other scenarios, as a consequence a higher exposure to risk may be expected. However, it is to be said that the failure of the emergency ventilation does not appear to cause something worse than it was before when the critical events associated to the release of toxic products or explosions (propane in bulk, or BLEVE) are investigated. Perhaps this result might be due to the fact that the ventilation system is designed in tunnels on the basis of reference fires (defined by standards) that have very higher probability to occur than toxic releases or explosions; as a result the state of not working correctly of the emergency ventilation might show scarce influence on the propagation of temperature and smoke caused by the aforementioned phenomena with very lower occurrence probability (for greater in-depth knowledge see, for example, Truchot and al. [26]).

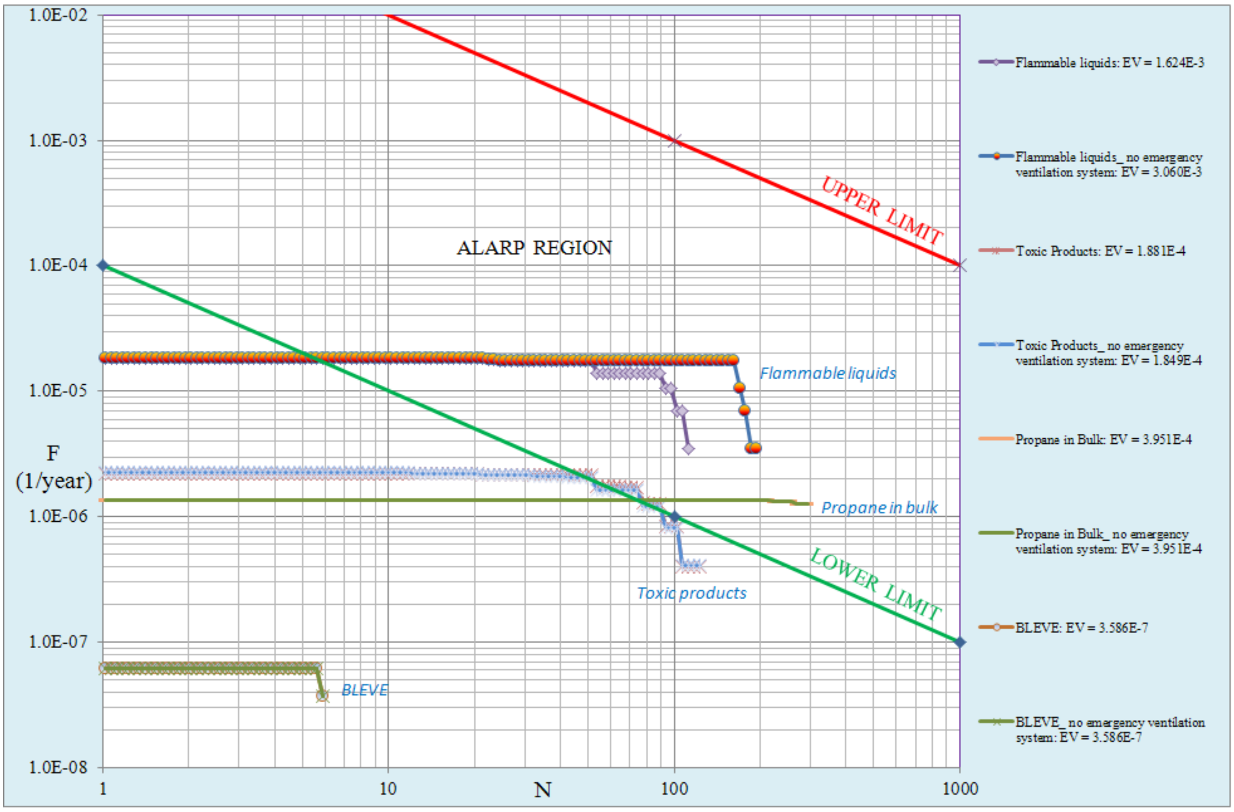

Fig. 3. F/N curves of aggregated scenarios for dangerous goods vehicles (DGVs) if the emergency ventilation system does not work (VHP = 3200 veh./h).

4.2. Alternative route running completely in the open air

In this paragraph, the results obtained for the route including the tunnel investigated are compared to those of the alternative route that runs completely in the open air in order to understand whether an increase or decrease in the risk level can be expected for the

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circulation of dangerous goods vehicles (DGVs). Figure 4 shows these two routes. The former (route 1) runs in the open air on a viaduct, then enters the tunnel, and is eventually in open air again (its length is divided as follows: 60% in the viaduct, 29% in the tunnel, 11% in the open air). The latter (route 2) runs completely on open roads and passes through a highly populated urban area. For these two routes we assumed the same total length (L = 4 km), traffic, and population density (3,600 residents/km^2) in order to make a more appropriate comparison in the quantitative risk analysis method.

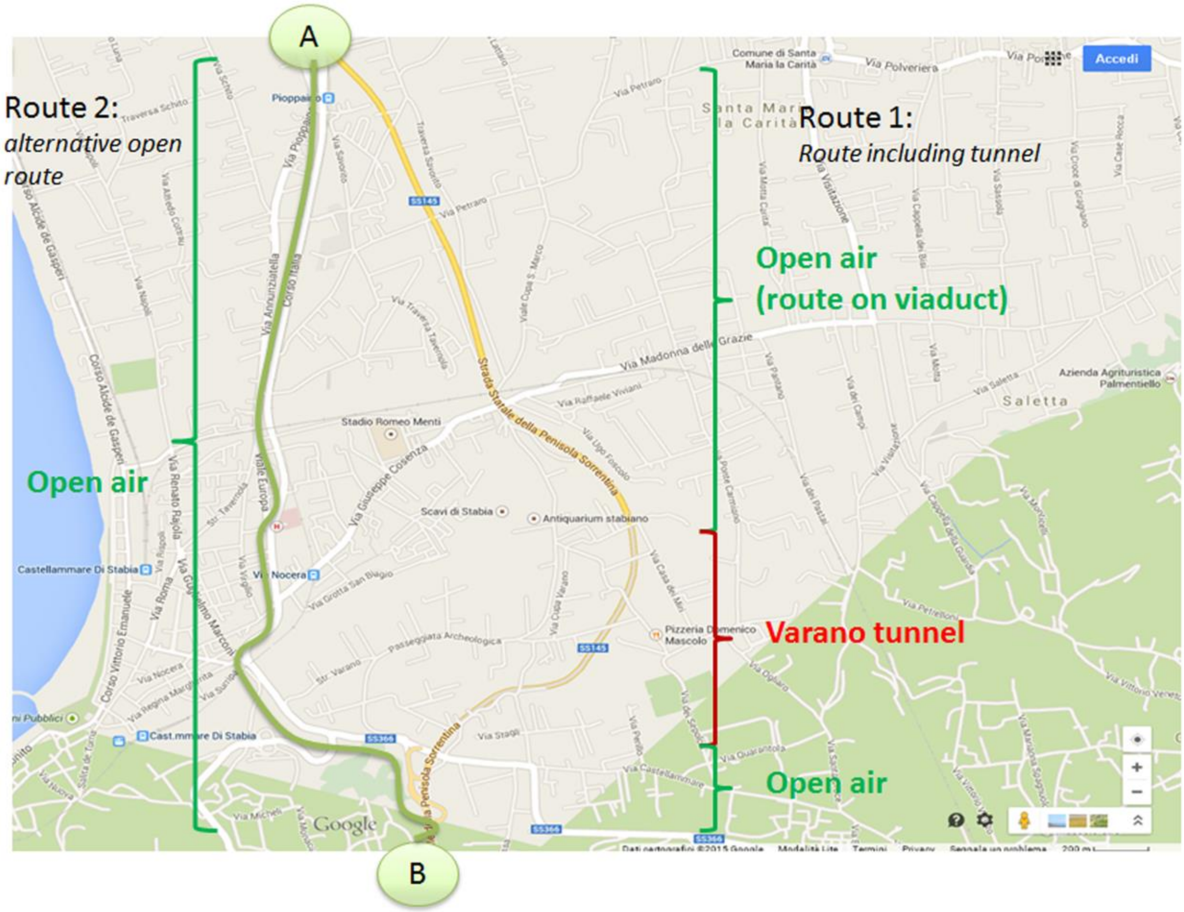

Fig.4. Maps of the two alternative routes [copyright Google]

Figures 5 and 6 show that the risk curves of the tunnel were found to lie both above and below those of the alternative open route depending on the type of dangerous goods transported. In particular the risk level for the exposed population was found to be higher in the route containing the tunnel for the two scenarios corresponding to the transport of LPG with which fire (no explosion) or motor spirit pool fire are associated. On the contrary in the open air the following scenarios were found to be more dangerous, namely the transport of LPG with which an explosion, ammonia release, or acrolein release are associated.

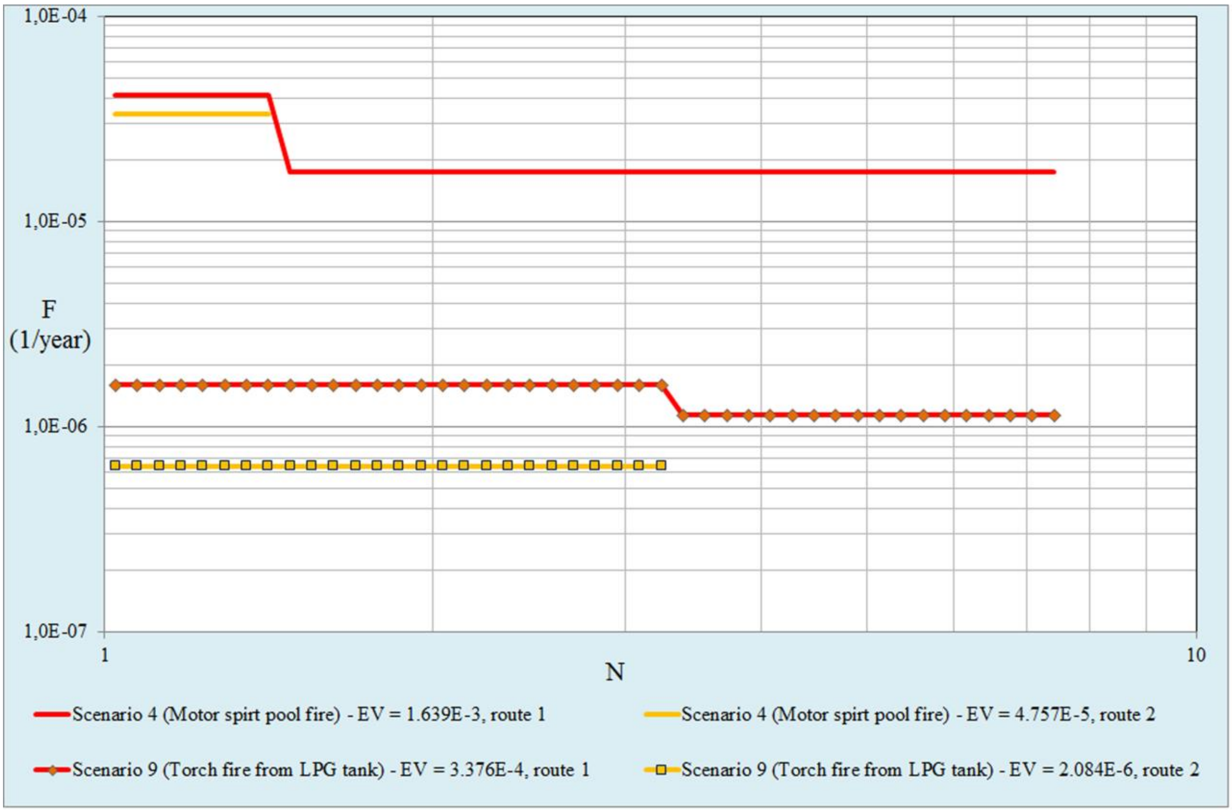

Fig. 5. F/N curves for the transport of LPG with which fire (no explosion) is associated, or motor spirit pool fire, for route 1 (including the tunnel) and route 2 (alternative itinerary running completely in the open air).

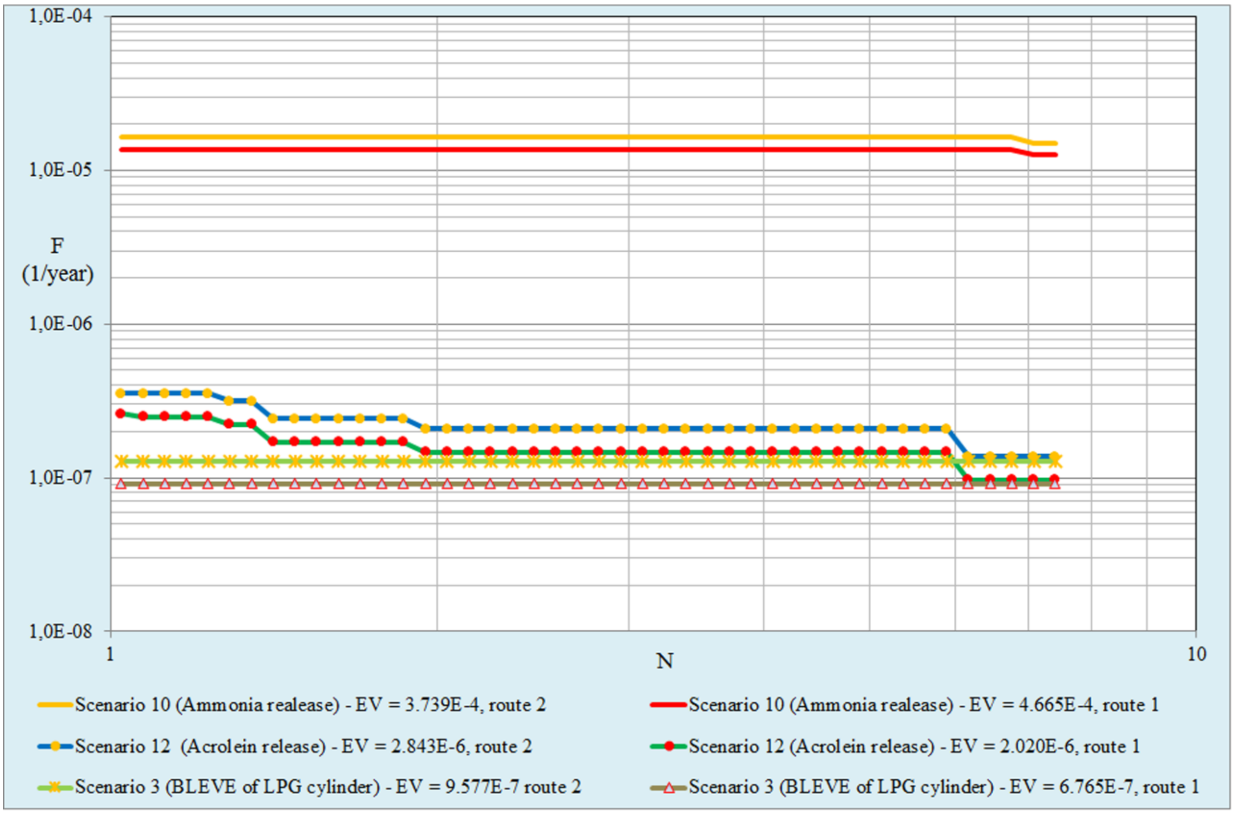

Fig. 6. F/N curves for three scenarios: transport of LPG with which an explosion, ammonia release, or acrolein release, for routes 1and 2 are associated.

This suggests that one should be wary before claiming that for the transport of dangerous products an open itinerary might be used if this passes through a highly populated area. In this case, a form of notice, for example, might be submitted to the TMA for approving the possibility of their circulation through the tunnel by night and/or under escort.

5. Lessons learned

Researchers are expending some energy in trying to determine which methodological approaches are the best for the quantitative risk analysis in tunnels. Discussions on methods applied over time with their strengths and weaknesses, as well as new frontiers and future directions of research, are often made. However, generally speaking all methodological approaches have limitations and the superiority of one model over another cannot be proven mathematically. Moreover empirical generalizations cannot be made because the results have been obtained by being based on geometric and traffic characteristics, as well as equipment, that are typical of the place studied.

With reference to the DG-QRAM, the strengths are based more especially on the possibility of selecting several risk scenarios as a function of hazardous goods transported by vehicles, and taking into account the main geometric and traffic characteristics of tunnel. Moreover, it is helpful when one has to compare the risk level found in tunnel to threshold values of intolerable risk, as well as to alternative routes running completely in open air. In other words, the tool used in our study appears to be helpful in the decisions-making process. In this respect, in fact, the Tunnel Management Agency (TMA) can decide, by using the results of the DG-QRAM, if additional safety measures should be implemented (in order to neutralize the critical elements of system), and/or if the circulation through the tunnel of vehicles carrying dangerous goods should be forbidden, permitted during specific time periods, and/or escort the DGVs.

However, it is to be said that some provisions of the European Directive 2004/54/EC cannot be modelled in the current version of the DG-QRAM (e.g. lay-bys and/or emergency stations, cross-connections for emergency services, water supply stations, specific road signs, and communication systems). Moreover the DG-QRAM appears to be unable to take into account that the speed of vehicles might be in tunnels higher than the imposed speed limit before entering the tunnel. Similarly, also the existing of Variable Message Signs (VMS) before entering the tunnel, which communicate to users the respect within the tunnel both of the imposed speed limit and the corresponding safety distance to vehicles ahead, cannot taken into account in the DG-QRAM. Additionally, it is to be said that the current version of the DG-QRAM does not seem to be compatible with the more recent version of the Microsoft Office system with which interfaces. All the aforementioned limitations leave the DG-QRAM user with the responsibility of accounting for the potential effects of parameters that cannot be modelled.

In parallel with the applications of the DG-QRAM, some proposals of development for this tool are beginning also to be present in the literature. For example, the extension to the study of longer routes by means of collecting the road characteristics and population data with the help of a geographic information system (GIS) (see for details, e.g., Ruffin et al. [27]). Concerning the human factors, which affect the performance of tunnel operators in the control centre during a critical event, it might be helpful evaluating the operators' response time by means of mathematical methods (e.g. the fuzzy logic system is used in Kyritopouolos et al.[28]). On the other hand, a more comprehensive quantitative risk analysis should also involve both critical events and traffic accidents (in this respect, the methodology proposed by Schubert et al. [29] utilizes Bayesian Probabilistic Networks for the risk assessment). However, too few studies are hitherto available in order to propose a more modern version of the quantitative risk analysis in tunnels.

In the light of the above considerations, the main lesson learned is that the DG-QRAM, which is widely-used in Europe, should be improved for updating and extending the quantitative risk analysis on which it is based. In this respect, an international research project should be launched and financial resources should be made available. This should involve many countries for sharing information and results observed in order to make the additional developments that at the moment are strictly necessary to the risk analyst.

6. Summary and conclusions

A quantitative risk analysis associated with dangerous goods vehicles (DGVs) running through road tunnels was performed. Heavy goods vehicles (HGVs) only for comparison reasons were also considered. The research made use of the DG-QRAM software, which was

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developed in Europe, in order to explore more especially the influence of traffic that can vary seasonally and/or during the day expressed in terms of peak hourly volume (VHP), as well as the percentage of freight vehicles, on the risk level of a specific bidirectional road tunnel. A possible temporary stop of the emergency ventilation system was also investigated. Finally, a comparison with an alternative route running completely in the open air was made.

The results in terms of social risk, as expressed by the F/N curves, show that all cases investigated are within the Italian ALARP limits. However risk levels were found to be higher for the HGVs (HRR = 20-100 MW) than for DGVs. This might be attributed to the fact that these vehicles travel with a greater frequency through tunnels compared with dangerous goods ones (i.e. the proportion of HGVs in traffic flow is much higher than that of DGVs), and as a consequence a greater exposure to risk is expected. Moreover, for a similar scenario lower risk levels are found to occur by night (i.e. when the peak hourly volume is lower). Therefore, in order to increase the safety level in tunnels the Tunnel Management Agency (TMA) might allow the circulation of dangerous goods more especially during this time period (e.g. from 22.00 p.m. to 6.00 a.m.).

An increase, for example, from 5 to 10% in the percentage freight vehicles, shows that for the DGVs an additional risk level can be found with the corresponding F/N curves closer to the Italian upper ALARP limit, but does not exceed it.

For a temporary stop of the emergency ventilation system, the F/N curves of the dangerous goods vehicles are still within the ALARP region. However, the F/N curve of flammable liquids lies over the F/N curves associated to an explosion or release of toxic products. This might be due to the fact that the occurrence frequency of fire with flammable liquids is higher than that of other scenarios, as a consequence a higher exposure to risk may be expected

The risk curves of the tunnel investigated were found to lie both above and below those of the alternative route running in the open air depending on the type of dangerous goods transported. In particular, the risk was found to be higher in the route including the tunnel for the LPG with which fire (without explosion), or motor spirit pool fire may be associated. On the contrary, the risk level for the exposed population was found to be higher for the alternative route in the following three scenarios, namely LPG with which explosion, ammonia release, or acrolein release may be associated. Therefore, one should be wary before claiming that for the transport of dangerous products an alternative itinerary in the open air might be used if this passes through a heavily populated area. In this case, a form of notice might be submitted to the TMA for approving the possibility of their circulation through the tunnel by night and/or under escort.

Although this paper may represent an interesting advancement in quantitative risk assessment on the transport of both dangerous goods through bidirectional road tunnels, certain points still remain that are worth investigating. In particular, it is to be said that some provisions of the European Directive 2004/54/EC cannot be implemented in the current version of the DG-QRAM (e.g. lay-bys and/or emergency stations, water supply stations, specific road signs, and communication systems). This leaves the DG-QRAM user with the responsibility of accounting for the potential effects of these parameters that cannot be modelled. Additionally, it is to be said the aforementioned DG-QRAM should also be updated in order to take into account also the event which are not considered in the Directive in order to achieve a more comprehensive quantitative risk analysis.

Therefore, further research should be addressed towards studies for making these additional developments possible. In this respect, an international research project should be launched.

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