Quantitative Risk Analysis based on the Impact of Traffic Flow in a Road Tunnel

C. Caliendo and M. L. De Guglielmo

Abstract— A quantitative risk analysis based on the impact of hourly traffic volume (VHP) and percentage of heavy goods vehicles (HGVs) in a bi-directional road tunnel was carried out both for normal and temporary traffic regimes. The results in term of social risk, as F/N curves, show that the risk level for combinations of VHP and percentage of HGVs can be beyond the threshold of intolerable risk. As a result, safety measures in order to reduce the risk level must be taken. In this respect, the Tunnel Management Agency (TMA) can permit, for normal traffic conditions, that HGVs pass through the tunnel only during night or along an alternative route runs completely in open air. Also in the event of a temporary lane closure for maintenance needs, the risk level can be beyond the safety limit. Risk charts are proposed for assisting the TMA in making decisions on traffic control strategies.

Keywords— Bi-directional traffic flow, Freight vehicles, Quantitative risk analysis, Road tunnel, Temporary traffic regime.

I. Introduction

Risk analysis is an important tool that can be helpful for improving and/or optimizing the safety level of road tunnels.

In this respect, it is to be said that the European Parliament and Council adopted the European Directive 2004/54/EC [1] in which it is clearly required, when a tunnel is opened for example to the transport of dangerous goods, that a risk analysis should be carried out to establish whether additional safety measures and/or supplementary equipment are necessary to ensure a high level of tunnel safety.

The Italian Ministry of Infrastructure and Transports [2] has also adopted the aforementioned Directive, and subsequently the Italian Management Agency of National Roads and Motorways (ANAS) has published guidelines [3] for the design of safety in Italian road tunnels. In this regard, a quantitative risk analysis (QRA) is often considered.

A quantitative risk analysis is generally based on a probabilistic approach that involves the identification of hazards, the estimations of probability and consequences of each hazard, and the quantification of the risk as the sum of probabilities multiplied by consequences. According to this approach, QRA includes event trees, fault trees and consequences estimation models. Social risk (e.g., the expected number of fatalities in the tunnel per year) is assumed to be the main output of QRA. Different risk models exist in the literature, however in many European countries (e.g. Austria, Switzerland, France, and Greece) the QRAM (Quantitative Risk Assessment Model), which was proposed jointly by PIARC and OECD (Organization for Economic Co-operation and Development) with associated software developed by INERIS [4], is the one most widely used.

Applications of QRAM can be found more especially in Saccomanno and Haastrup [5], Knoflacher and Plaffenbichler [6], Hall et al. [7], Parson Brincherhoff Quade & Douglas [8], Kyritopouolos et al. [9], Diernhofer et al. [10], Steiger et al. [11], Di Santo et al. [12]. In Petelin et al. [13], furthermore, the application of QRAM take into account the circumstance in which a tube is temporarily closed to traffic for rehabilitation and the other one is temporary affected by bidirectional traffic. Recently also Caliendo and De Guglielmo [14]-[15] have used the aforementioned QRAM for investigating on the impact of dangerous goods vehicles (DGVs) travelling through a bi-directional road tunnel. In particular, seasonal variation of traffic, speed of vehicles, and failure of emergency ventilation system were investigated. In this respect, a comparison with heavy goods vehicles (HGVs) was also made. Moreover the risk associated with an alternative route running completely in the open air was also evaluated. However, it is to be stressed that in Caliendo and De Guglielmo [14] the impact on the social risk level in tunnel due to the variability both of traffic during day and percentage of freight vehicles (heavy goods vehicles without dangerous goods) were not investigated in a great depth.

Hourly traffic volume can have a significant role on the social risk level in tunnels because as it increases, an increase both in the frequency of accidents and in the number of fatalities, may be expected. Moreover the presence in tunnel of many vehicles, which act as obstacles, may also influence the temperatures and spreading of smoke, as well as the performance of the ventilation system in the event of a fire source. Likewise as the percentage of heavy goods vehicles (HGVs) increases, an increase in the number of accidents involving an HGV is expected. In addition, more severe accidents in terms of fatalities than ones involved only cars may also be believed to occur. It is to be noted that higher heat release rate (HRR) are also expected in the case of an HGV

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burning compared to cars. Therefore, there are reasons for evaluating the influence of the mentioned traffic parameters in more detail.

The present paper mainly aims at investigating road tunnels with the intent of showing among different combinations of the hourly traffic volume (VHP) and percentage of heavy goods vehicles (%HGVs).

An additional purpose of this paper is to assess the level of risk in event of a lane closure for maintenance needs. Since the studied tunnel has two lanes with bi-directional traffic, it appeared to be interesting understanding what might happen if vehicles travelled only along the other lane (unidirectional traffic) and in the opposite direction of airflow (provided by the longitudinal ventilation system).

The tool used in the paper is based on the quantitative risk analysis; in particular, the aforementioned QRAM with associated software has been applied. The results obtainable might help decision-makers in implementing additional safety measures or individualizing more appropriate solutions in terms of traffic control strategies for the tunnel investigated (e.g., understanding when to allow or limit the circulation of HGVs; or if it is safer to close the whole tunnels in the case of maintenance needs).

In the light of the above considerations, this article is organized as follows: the next section contains a model description of scenarios implemented in QRAM. The results of computer simulations are then presented and discussed, and an evaluation of safety level is made. Risk charts are also proposed for quickly assisting decision-makers. Finally, the conclusions and directions of future research are reported.

II. General concept of risk

Generally speaking, the risk (*R*) is given by the product of probability or frequency (*F*) of a critical event multiplied by its consequences (*C*): $R=F\cdot C$.

If $F(N)$ denote the frequency [1/year] of an event that causes N or more victims (in term of number of fatalities and injuries), the social risk can be defined as follows: $SR=F(N)\cdot N$.

The social risk has a graphic representation by means of F/N curves in a bi-logarithmic chart and a numerical value, the expected value of risk or EV, that can be calculated as integral between 1 and the maximum possible number of victims N in a certain time period:

$$EV = \int_1^{+\infty} F(n)dN \quad (1)$$

With reference to risk in road tunnel, the results of analysis in term of F/N curves need to be compared to a pre-selected safety limit. If the F/N curve results above the chosen safety limit (threshold of intolerable risk), safety measures for risk reduction must be taken. When the F/N curve lies below the threshold of intolerable risk, the possibility of implementing additional safety measures should be justified by an appropriate cost-benefit analysis.

III. Tunnel and QRAM description

A. Tunnel description

In order to achieve the above mentioned 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) which connects the cities of Castellammare di Stabia and Sorrento.

The tunnel, which is a curved bi-directional road tunnel with one lane per direction, 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 (from Castellammare to Sorrento).

The ventilation system will be constituted by 8 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.

B. Traffic

Available traffic data were expressed in terms of annual average daily traffic (AADT): 20,000 vehicles/day for the bidirectional flow with an average percentage of heavy vehicles equal to 5%. Based on these data we estimated a maximum peak hourly volume (VHP) of 3200 vehicles/hour in ordinary traffic regime (bidirectional flow) and a maximum VHP of 1700 vehicles/hour in event of a lane closure for maintenance needs (unidirectional flow from Sorrento to Castellammare). This happens more especially in summer (from June to August) because this tunnel is part of a road serving a city by the sea. A minimum VHP of 500 vehicles/h was also assumed.

In other words, it is to be said that this tunnel becomes oversaturated during the peak summer periods and may be little used during the remaining part of the year. Therefore the range of hourly traffic volume investigated is between 500 and 3200 veh./h for bidirectional flow, and between 500 and 2000 vehicles/h when the unidirectional flow is considered.

The percentage of heavy goods vehicles (HGVs) was assumed to range from 5% to 20%. The imposed speed limit for the Varano tunnel is 50 km/h and vehicles are forbidden to overtake.

C. Previous studies

With reference to the aforementioned tunnel, it is to be said that in previous studies, Caliendo et al. [16]-[17] the effects of a fire source due to a different heavy goods vehicle with or without traffic, with heat release rate peaks of 8, 30, 50 and 100 MW by using a computational fluid dynamic (CFD) modeling were more especially investigated. Subsequently, in

Caliendo et al. [18] the findings obtained by means of a simulation model for representing an evacuation process of people from the tunnel in the event of a fire was also described. In this respect, Briano et al. [19]-[20] also have investigated on the evacuation process from road tunnels using simulation models.

Finally, in the already mentioned Caliendo and De Guglielmo [14], a quantitative risk analysis considering 13 scenarios was carried out. In that paper, it is to be specified that the social risk for two scenarios without dangerous goods (HRR= 20 MW and HRR = 100 MW) was found to be higher than that for DGVs. This was attributed to the fact that HGVs travel with greater frequency through tunnel compared to DGVs. In the light of that finding, in the present paper, in order to save space, we comment only the results concerning the impact of VHP and percentage of freight vehicles on the social risk associated to the aforementioned two scenarios without dangerous goods under bidirectional and unidirectional traffic conditions.

D. *QRAM*

A complete assessment of the quantitative risk analysis on the transport of goods through tunnels would include considering all kinds of materials and/or whether vehicles are fully or partially loaded. Since not all cases can be considered in analysis, simplifications are generally made. In this respect, the QRAM software considers 13 accident scenarios. Two scenarios are concerning heavy goods vehicles (HGVs) with no dangerous goods (HRR = 20 MW, and HRR = 100 MW), while the remaining scenarios consider dangerous goods vehicles (DGVs). The QRAM takes into account: accident frequencies; consequences of incidents, escape and sheltering effects; and effects of hazards (such as heat and smoke) on people. A wide range of information has also to be introduced as input in the QRAM (e.g., geometry, traffic, ventilation system, drainage, emergency escape, density of population). The results for each scenario are reported in terms of social risk by means of F/N curves. Each curve can synthetically be illustrated also in term of a single value representing the average number of fatalities per year, EV.

IV. Analysis of Results

In this paragraph the results of the QRAM applied to assess the social risk level corresponding to two scenarios with HRR = 20 MW and HRR = 100 MW are reported as a function of the VHP and percentage of heavy goods vehicles (%HGVs) both for normal and temporary traffic regimes (i.e. in the event of a lane closure). According to the Italian Ministry of Infrastructure and Transports [2], the safety limit is specified to be that where the threshold values for intolerable risk are between 10^{-1} and 10^{-3} respectively for N = 1 and N = 100 fatalities.

A. *Normal traffic regime*

In normal traffic regime (i.e. bidirectional flow), the results reported in figure 1 show that, with reference to the scenario with HRR = 100 MW, the first F/N curve that touches the safety limit is that with VHP = 1600 veh./h and a percentage of heavy goods vehicles equal to 20%. For VHP > 1600 veh./h, and in particular VHP = 2100 veh./h, the F/N curve for the scenario with HRR = 100 MW exceeds the safety limit and that for the scenario with HRR = 20 MW and a percentage of HGVs=20% touches the safety limit too. For VHP = 2400 veh./h, the F/N curves corresponding to the scenarios with HRR = 100 MW and HRR=20 MW exceed the safety limit when the percentage of HGVs is 15 and 20%, respectively. Finally for VHP = 3200 veh./h, the F/N curve for HRR = 100 MW and percentage of trucks equal to 10% is very close to the safety limit, and the F/N curve for the scenario with HRR=20 MW and percentage of HGVs = 15 % exceeds the safety limit. In synthesis, these results indicate that the tunnel investigated might operate beyond the chosen safety limit (i.e. safety measures for risk reduction must be taken) for traffic conditions in which VHP ≥2 100 veh./h and the percentage of HGVs is ≥ 20%; or for VHP ≥ 2400 veh./h and with a percentage of HGVs ≥ 15%. Note that for VHP = 3200 veh./h, we are very close to the safety limit already when the percentage of HGVs is 10%; also in this case measures precautionary would be desirable.

The aforementioned combinations of VHP and percentage of HGVs should be taken into account in the tunnel management. In this respect, it is to be suggested that the Tunnel Management Agency (TMA), in the circumstances of higher VHP and percentage of freight vehicles (i.e. in summer, in the case investigated) can permit that HGVs pass through the tunnel only during night (e.g. from 22.00 p.m. and 6:00 a.m.). In this regard, in fact, we estimated a peak hourly traffic volume of 1100 veh./h during night. Based on this lower value of VHP, we found that all the F/N curves are below the safety limit for all the percentages of HGVs investigated (see Figure 2). In alternative, the TMA could permit the circulation of HGVs during day along a route that, forming a by-pass for the tunnel investigated, runs completely in open air.

B. *Expected Risk (EV) Regions*

In this section, with reference to the two aforementioned scenarios (HRR = 20 MW, and HRR =100 MW), the corresponding regions regarding the average number of fatalities per year, (i.e. the expected value EV) as computed by the QRAM software, are reported for different combinations of VHP and percentage of HGVs (bi-directional flow). Figure 3 and Figure 4 show that some regions, specified by contour lines, can indicate safe conditions for the tunnel investigated and others an unsafe status.

In particular for the scenario with HRR = 20 MW, the area of intolerable risk involves the corresponding regions 4 (EV = 1.50E-01 ÷ 2.00E-01) and 5 (EV = 2.00E-01 ÷ 2.50E-01), and a very small part of the region 3 (EV = 1.00E-01÷1.50E-01).

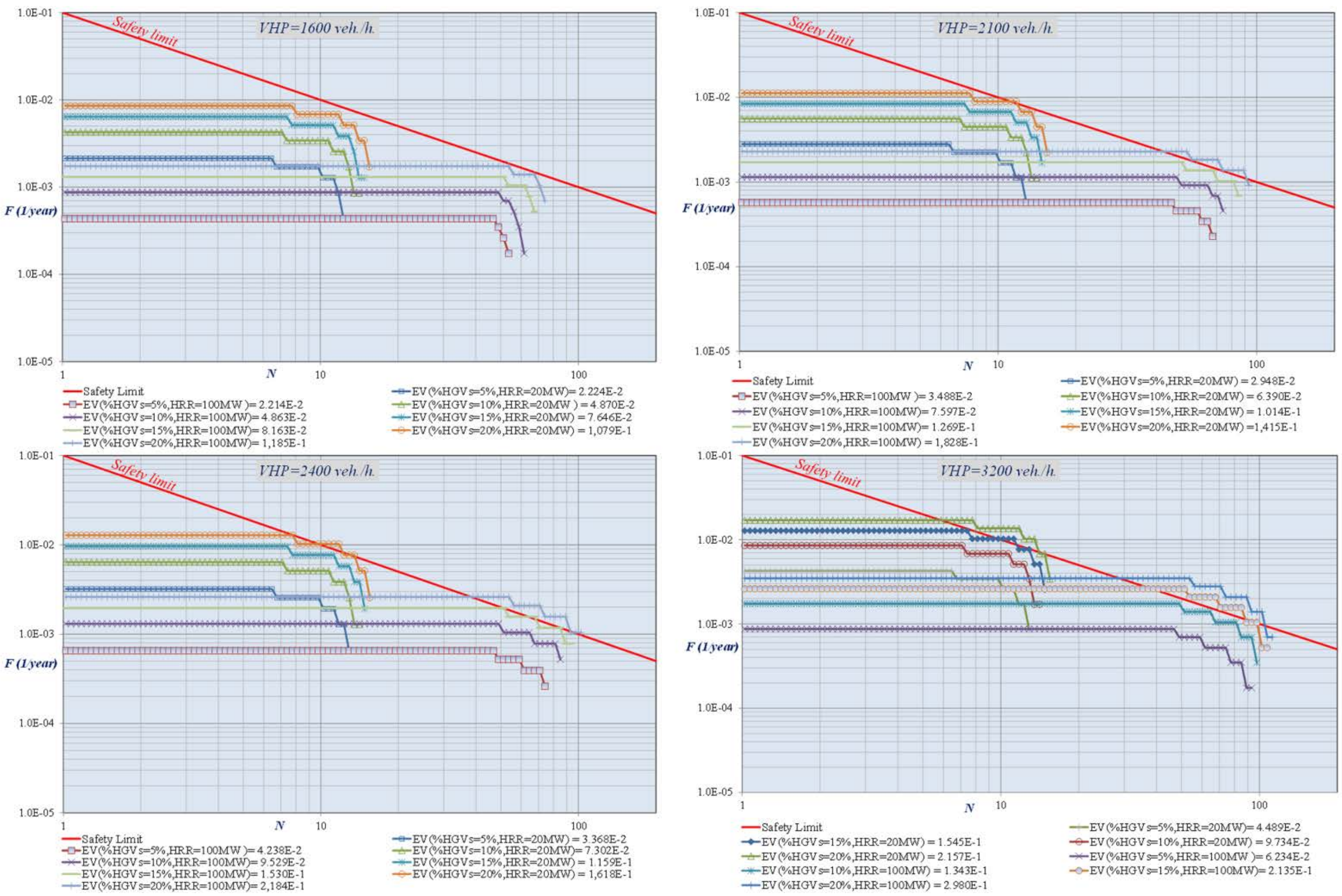

Fig. 1 F/N curves for 20 and 100 MW for different traffic conditions (from 1600 to 3200 veh./h. and from 5% to 20% of HGVs) in normal traffic regime.

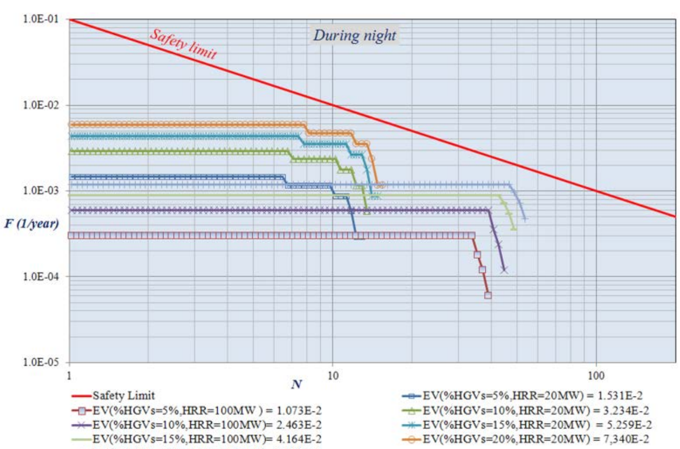

Fig. 2 F/N curves for traffic during night and for all percentages of HGVs (bi-directional traffic).

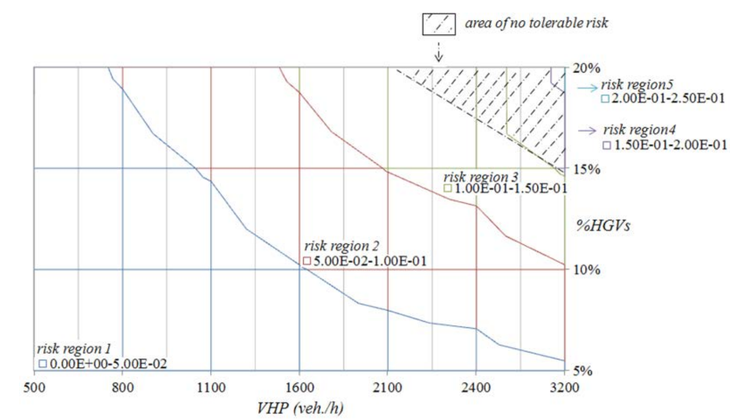

Fig. 3 Regions of expected value (EV) of damage for HGV = 20 MW (bi-directional traffic).

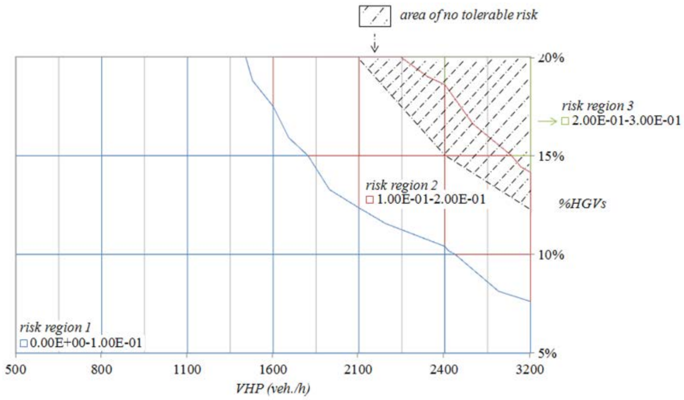

Fig. 4 Regions of expected value (EV) of damage for HGV =100 MW (bi-directional traffic).

As regards the scenario with HRR = 100 MW, the area of intolerable risk involves the region 3 (EV = 2.00E-01 ÷ 3.00E-01) and a significant part of the region 2 (EV = 1.00E-01 ÷ 2.00E-01).

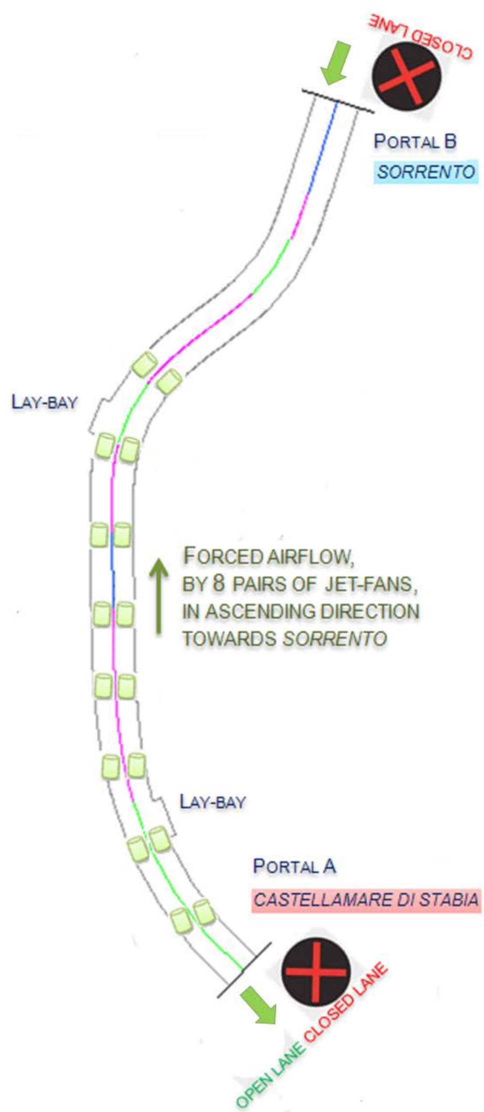

Fig. 5 Temporary traffic regime with a closed lane

These risk carts appear to be useful because can quickly assist the TMA in making preventive actions on traffic control. In fact, combinations of VHP and percentage of HGVs can cause that the tunnel might operate beyond the threshold of safety limit.

C. *Temporary traffic regime*

In temporary traffic regime (i.e. unidirectional traffic flow on a lane only in the opposite direction of airflow, see Figure 5), the results reported in Figure 6 show that, with reference to the scenario with HRR=100 MW, the F/N curve touches the safety limit when VHP=1600 veh./h and the percentage of heavy goods vehicles is equal to 20%.

For VHP > 1700 veh./h the F/N curve begins to exceed the safety limit. For VHP>1800 veh/h, this F/N curve is more significantly beyond the safety limit. Finally for VHP ≥ 2000veh./h, the F/N curve is very close to the safety limit also for a percentage of HGVs = 15%. With reference to the scenario with HRR=20 MW, the F/N curve corresponding to a percentage of HGVs equal to 20% touches the safety limit when VHP=2000veh./h.

D. *Expected Risk (EV) Regions*

With reference to the scenario with HRR = 100 MW, the corresponding region of risk are reported for different combinations of VHP and percentage of HGVs.

Figure 7 shows that, for a temporary traffic regime (i.e. a lane closure), the social risk can be in the area of no tolerable risk for VHP ≥ 1700veh./h and percentage of HGVs ≥ 20%.

This risk cart can help the TMA in making decisions in the event of maintenance needs. In other words in the aforementioned circumstances (i.e. VHP 1700 ≥ veh./h per lane and %HGVs ≥ 20%) the TMA might decide the whole tunnel closure because the use on a lane only is unsafe.

V. Conclusion

A quantitative risk analysis of a bidirectional road tunnel for different combinations of hourly traffic volume (VHP) and percentage of heavy goods vehicles (HGVs) was performed for normal and temporary traffic regimes.

The present study made use of the QRAM software developed in Europe.

The results in terms of social risk, as expressed by the F/N curves, show that in some cases the tunnel studied might operate beyond the chosen safety limit. This happens more especially for higher values of VHP and percentage of HGVs.

Risk charts, based on the expected risk (EV) as computed by the QRAM, are also presented.

These can quickly help the Tunnel Management Agency (TMA) to implement traffic control strategies in order to reduce the excessive risk. In particular, it is suggested that the TMA can permit, in summer, that HGVs pass through the tunnel only during night (e.g. from 22.00 p.m. and 6:00 a.m.).

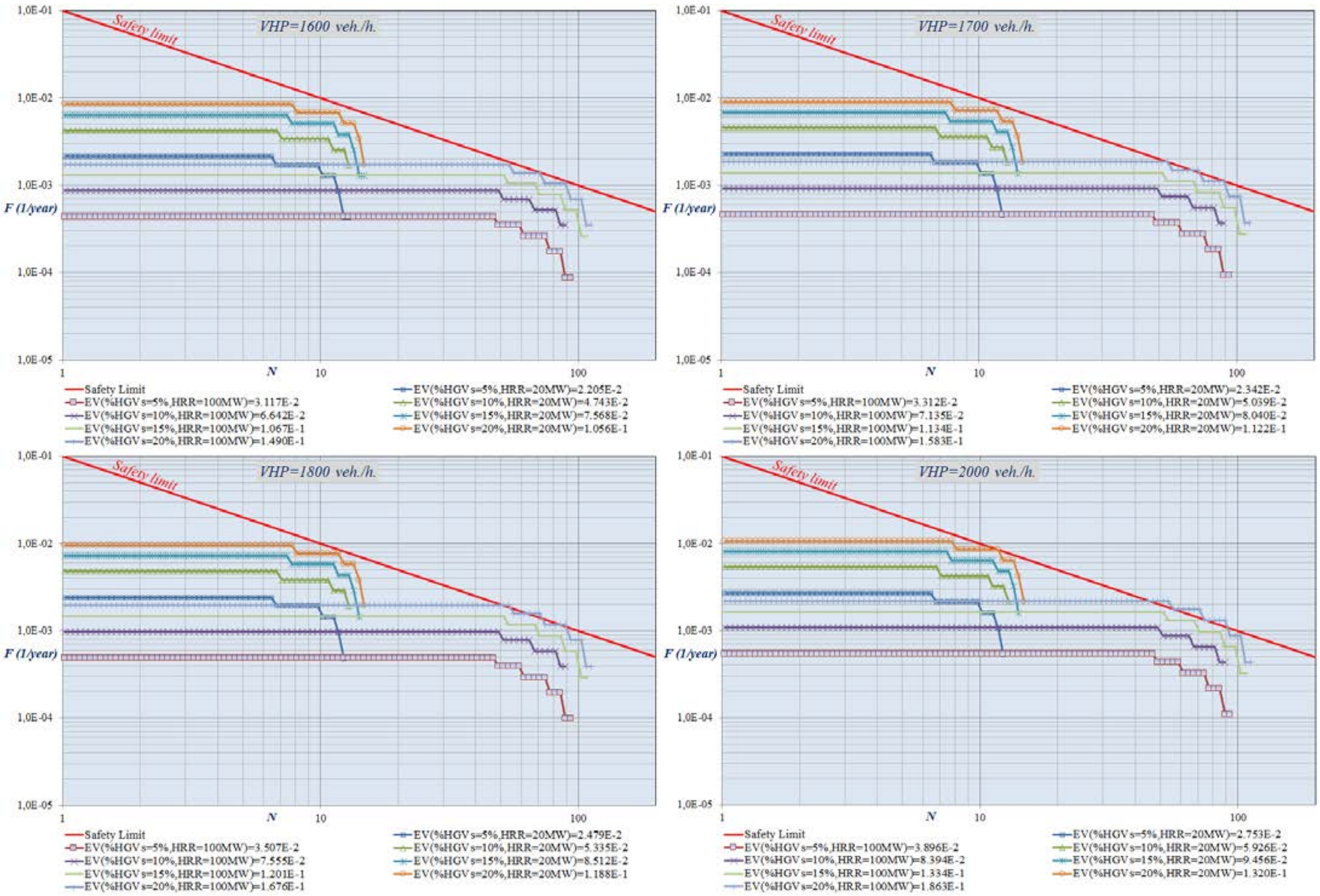

Fig. 6 F/N curves for 20 and 100 MW for different traffic conditions (from 1600 to 2000 veh./h. and from 5% to 20% of HGVs) in temporary traffic regime.

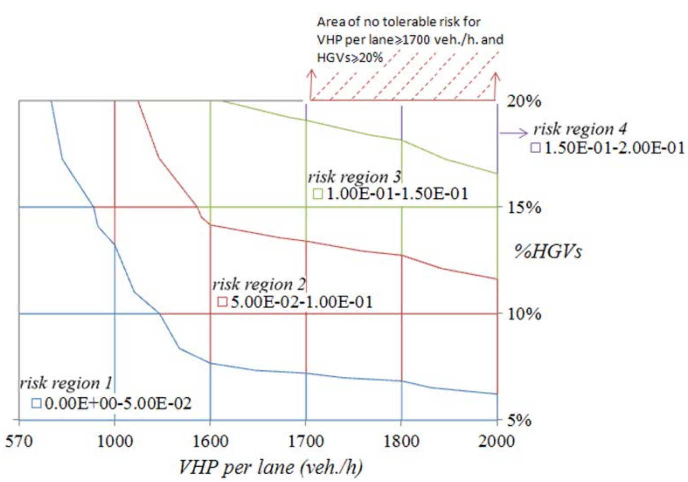

Fig. 7 Regions of expected value (EV) of damage for HGV = 100 MW in case of a closed lane (unidirectional traffic for maintenance needs).

In alternative, the TMA could permit the circulation of HGVs during day along an itinerary that, forming a by-pass for the tunnel investigated, runs completely in open air.

Furthermore, in the event of maintenance needs in the tunnel investigated, the TMA can understand if it is necessary the closure of a lane only or in alternative if it is safer the closure of the whole tunnel due to the different combinations of traffic in terms of VHP per lane and percentage of HGVs.

Although this paper suggests interesting implications for tunnel management, further studies should also be carried for a more consolidated verify of results obtained using also different risk analysis models.

References

[1] European Parliament and Council. Directive 2004/54/EC. Official Journal of the European Union. L.167, Bruxelles, April 2004.

[2] Italian Ministry of Infrastructures and Transports. Adoption of the Directive 2004/54/EC on the safety of tunnels belonging to the Trans-European Road Network. G.U., No. 235, October 2006.

[3] ANAS. Linee guida per la progettazione della sicurezza nelle gallerie stradali. Condirezione Generale Tecnica, Direzione Centrale Progettazione. Second Edition 2009. Italian.

[4] INERIS. Transport of dangerous goods through road tunnels. Quantitative risk assessment model (Version 3.60 and 3.61), 2005 User's Guide and Reference Manual.

[5] F. Saccomanno, P. Haastrup. Influence of safety measures on the risks of transporting dangerous goods through road tunnels. Risk Analysis 2002; 22(6): 1059-1069

[6] [6] H. Knoflacher, P.C. Pfaffenbichler. A comparative risk analysis for selected Austrian tunnels. Second International Conference Tunnel Safety and Ventilation, 2004 Graz (Austria).

[7] R. Hall., H. Knoflacher, P. Pons. Quantitative risk assessment model for dangerous goods transport through road tunnels. Road Magazine 2006, 329:87-93.

[8] Parson Brickerhoff Quade & Douglas, 2006. Risk Analysis study of hazardous materials trucks through Eisenhower/Johnson Memorial Tunnels. Final Report for Colorado Department of Transportation.

[9] K. Kirytopoulos, A. Rentizelas, I. Tatsiopoulos, G. Papadopoulos. Quantitative risk analysis for road tunnels complying with EU regulations. Journal of Risk Research 2010; 13(8), 1027-1041.

[10] F. Diernhofer, B. Kohl, R. Horhan. Risk assessment of transport for dangerous goods in Austrian road tunnels. 4th International Symposium on Tunnel Safety and Security, Frankfurt am Main, Germany, March 17-19, 2010; http://www.ilf.com/fileadmin/user_upload/publikationen/53_Risk_Assessment_Transport_Dangerous_Goods.pdf

[11] M. Steiger, N. Norghauer, J.R. Day. Quantified risk analysis of ventilation systems in road tunnels: simple portal-to-portal longitudinal ventilation versus local smoke extraction systems. Fifth International Conference Tunnel Safety and Ventilation 2010, Graz (Austria).

[12] C. Di Santo, K. Gkoumas, F. Bontempi. Risk analysis for severe traffic accidents in road tunnels (part I. Proceedings IF CRASC'15, University of Roma La Sapienza, May 14-16 2015.

[13] S. Petelin, B. Luin, P. Vidmar. Risk analysis methodology for road tunnels and alternative routes. Journal of Mechanical Engineering 2010; 56: 41-51.

[14] C. Caliendo, M. L. De Guglielmo. Quantitative risk analysis on the transport of dangerous goods through a bi-directional road tunnel. Under review for Risk Analysis

[15] C. Caliendo, M. L. De Guglielmo. Risk impact analysis of traffic volume and heavy goods vehicles in a bi-directional road tunnel. Proceedings of the 6th International Conference on Automotive and Transportation Systems (ICAT'15) published by WSEAS Press, 2015. ISBN 978-1-61804-316-0

[16] C. Caliendo, P. Ciambelli, M. L. De Guglielmo,, M. G. Meo, P. Russo. Numerical simulation of different HGV fire scenarios in curved bi-directional road tunnels and safety evaluation. Tunnelling and Underground Space Technology 2012a; 31: 33–50.

[17] C. Caliendo, P. Ciambelli, M. L. De Guglielmo,, M. G. Meo, P. Russo. Simulation of fire scenarios due to different vehicle types with and without traffic in a bi-directional road tunnel. Tunnelling and Underground Space Technology 2013; 37: 22–36.

[18] C. Caliendo, P. Ciambelli, M. L. De Guglielmo,, M. G. Meo, P. Russo. Simulation of people evacuation in the event of road tunnel fire. Procedia-Social and Behavioral Science 2012b; 53: 178-188.

[19] E. Briano, R. Revetria, A. Testa. Behaviour models for evacuation of a motorway tunnel, Proceedings of the 8th WSEAS International Conference on System Science and Simulation in Engineering, ISBN: 978-960-474-131-1.

[20] E. Briano, C. Caballini, R. Mosca, R. Revetria, A. Testa. Study of an emergency situation using 2D and 3D simulation models, WSEAS Trasactions on Systems, Issue 4, Volume 9, April 2010. ISSN:1109-2777.

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