A parametric risk analysis of goods transport through road tunnels

Ciro Caliendo, and Maria Luisa De Guglielmo

Abstract**—** A parametric study for evaluating the impact due to vehicles transporting dangerous goods on the risk level in road tunnels is presented. Unidirectional tunnels having characteristics in compliance with the European Directive 2004/54/EC were more especially investigated. Different combinations of tunnel length (L), annual average daily traffic (AADT), percentage both of heavy goods vehicles (HGVs) and dangerous goods vehicles (DGVs) were considered. The results, expressed in terms of social risk (as F/N curves) and expected value EV, show that the risk level is positively associated with: L, AADT per lane, percentages of HGVs and DGVs. Furthermore, certain F/N curves were found to be beyond the threshold of intolerable risk for higher percentages of HGVs and DGVs; as a consequence, additional safety measures must be implemented. A radar chart is also proposed in order to help Tunnel Management Agencies (TMAs) in making more appropriate decisions in traffic control strategies concerning more especially DGVs.

Keywords- Quantitative risk analysis, Unidirectional road tunnels, Dangerous goods vehicles.

I. Introduction

THE transport of dangerous goods (DGs) by road has a relevant importance for safety both on open roads and in tunnels. According to recent statistical data [1] most States in the EU-28, with a major economy, have a share of dangerous goods, in the total road transport of goods, between 4% and 8%. Despite statistics show that, for most countries and also for Italy, more than one-half of the transport of DGs is performed on national territory, the ability to move these specific goods safely, quickly and cost-efficiently among European markets still remains crucial for international trade and economic development. The road transport of dangerous goods throughout the inland regions of the European Union is recently governed by Directive 2008/68/EC [2] and further back, from 1957, by European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) [3]. The uniformity in regulations has the aim to permit free movement of DGs at an acceptable level of safety anywhere in Europe. Since Member States are also able to apply additional measures or safety requirements to their infrastructures and also restrictions to the passage of dangerous goods vehicles (e.g. in the light of ADR), an unequal protection level again the risk for users might be produced. For avoiding this circumstance, in 2014, the European Commission has promoted a study in order to harmonizing the risk acceptance criteria (RAC) among Member States [4]. The term RAC indicates the critical elements that are output of lager methodologies that analyse risk and define how it can be assessed and managed by a decision maker.

For road tunnels, the indicated study proposed as RAC the use of: 1) societal risk criteria expressed as FN curves for the exposed populations, where F is the cumulative frequency that the number of fatalities is equal or greater than the given number N; and 2) ALARP criteria for defining what is *As Low As Reasonably Practicable* by means of safety measures that take into account their costs respect to a possible benefit of associated risk reductions.

The methodological approach that appears to be more appropriate in taking into account the aforementioned criteria is the quantitative risk analysis (QRA).

The Italian Decree 2006/264 [5], which formally accepts the Directive 2004/54/EC [6] on minim safety requirements in road tunnels, suggests a QRA procedure. Then certain guidelines for the design of road tunnels safety, which detail a specific QRA for Italian tunnels, were published [7].

Different models for carrying out a QRA are used in various countries as summarized in [8]. In Europe, for the risk analysis of DGVs only (i.e., it is not strictly appropriate for vehicles that does not carriage dangerous goods) is widely used the DG-QRAM (Dangerous Goods-Quantitative Risk Model) proposed jointly by PIARC (Permanent International Association of Road Congress) and OECD (Organization for Economic Co-operation and Developed) with associated software developed by INERIS [9].

According to the international literature, applications of the DG-QRAM can be found more especially in the following studies in chronological order: Saccomanno and Haastrup [10]; Knoflacher and Plaffenbichler [11]; Hall et al. [12], Parson Brincherhoff Quade & Douglas [13]; Petelin et al. [14]; Kyritopouolos et al. [15]; Steiger et al. [16]; Diernhofer et al. [17]; Zulauf [18]; Ronchi et al. [19]; Zhou et al. [20]; Caliendo and De Guglielmo [21][22], Vagiokas et al. [23].

Caliendo and De Guglielmo [24], more recently, have carried out a QRA on the transport of dangerous goods, through a bidirectional road tunnel, in order to show the impact due to both different peak hourly traffic volumes and

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failure of ventilation system. A comparison with an alternative route running completely in open air was also made. In a further study [25], the authors investigated, instead, on unidirectional road tunnels for different percentages of dangerous goods vehicles (DGVs).

However, it is to be said that the aforementioned applications of QRA contained in literature give attention to some parameters affecting the risk level in road tunnels only. A wider assessment of the risk caused by a rise in the amount of dangerous goods vehicles (DGVs) for different situations of annual average daily traffic (AADT), heavy goods vehicles (HGVs), and tunnel length (L) does not appear to have been sufficiently analysed.

Therefore, the intent of the present study is to provide additional developments to our knowledge by means of a parametric study on the risk levels in unidirectional tunnels designed with characteristics in compliance with the European Directive 2004/54/EC. With respect to the purpose of this article, different combinations of the percentage both of DGVs and HGVs, as well as of AADT per lane and tunnel length (L), were investigated. This was made also for understanding if the results obtainable might contribute to gaining new insights for Tunnel Management agencies (TMAs) in control traffic strategies regarding more especially the transport of DGVs.

The next section of the present paper contains a description of the methodology applied; while the subsequent section deals with the tunnels investigated. Then the results are shown and compared to the Italian risk thresholds. Finally, a radar chart is proposed and conclusions are commented on.

II. METHODOLOGICAL APPROACH

An appropriate approach for risk analysis in road tunnels is the quantitative risk analysis (QRA) that differs from the qualitative risk analysis for including a lower uncertainty level. The most used method is the probabilistic one because of the impossibility to always have exact input parameters, that are needed by the deterministic method for giving accurate results. The 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. The most widely used output of QRA is the social risk expressed in terms of F/N curves (where F is the cumulative probability and N the number of fatalities) and the expected value EV (integral between 1 and the maximum possible number of victims N in a certain period). However, the results of risk analysis need to be compared with threshold values of tolerable and intolerable risk.

In this respect, according to the Directive 2004/54/EC [6], each single Member State has to define its own limits. The Italian Ministry of Infrastructure and Transports [5] has specified that the threshold values for intolerable risk are considered between 10^{-1} and 10^{-3}, for N=1 and N=100 fatalities; whereas the threshold values for tolerable risk are between 10^{-4} and 10^{-6}, respectively, for N=1 and N=100 fatalities; as a result, the Italian ALARP region is individualised by these limits.

If the F/N curve is above the chosen safety limit (threshold of intolerable risk), safety measures for risk reduction must be taken independently of their costs. When the F/N curve lies below the threshold of the tolerable risk, additional safety measures are not necessary. Between these two risk thresholds the ALARP area represent the area of conditional tolerable risk (additional safety measures should be justified by a cost-benefit analysis).

A complete assessment of the quantitative risk analysis on the transport of dangerous goods vehicles (DGVs) through tunnels would include considering all kinds of dangerous materials and if vehicles are fully or partially loaded. Since all circumstances cannot be investigated, simplifications have made. In this respect, we used the DG-QRAM software.

It considers 13 accident scenarios, 11 of which are concerning DGs: explosions of different sizes, release of toxic products (medium and large releases) and fires that can be caused by some flammable liquids. For more details on reference scenarios and DG-QRAM software, the reader can refer to a previous study [22].

The output used in this paper is in the form of the aggregate scenario. In other words, all the 13 DG-QRAM scenarios are grouped together in one single F/N curve and expected value EV.

III. TUNNELS INVESTIGATED

According to the Directive 2004/54EC [6] two types of unidirectional tunnels, based on the tunnel length (L), were considered at the design stage: $1000 < L \leq 3000$ m, and $L > 3000$ m. In particular, we decided to investigate on tunnels with L = 2 Km and L = 4 km, respectively. Also the annual average daily traffic (AADT) per lane was considered in compliance with the Directive. In fact, we assumed values of 5000 and 10,000 vehicles/ day, respectively. Moreover, the following different percentages of HGVs were assumed: 10, 20 and 30%; while for the DGVs we used 1, 12 and 24%. In other words, the parametric analysis involved 36 different risk scenarios. Figure 1 gives a view of the possible combinations of parameters investigated. Figure 2 shows, instead, the common characteristics assumed in this study (cross-section, longitudinal slope, lighting and ventilation systems, emergency exits, monitoring, and traffic signals).

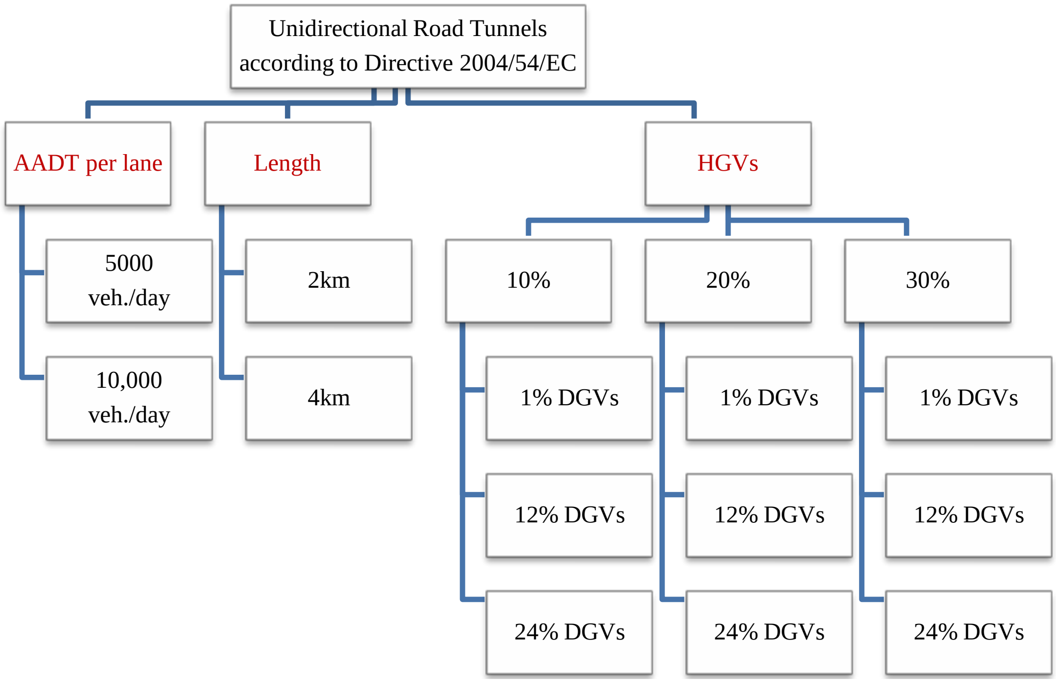

Fig. 1 View of the possible combinations of parameters investigated (36 different risk scenarios).

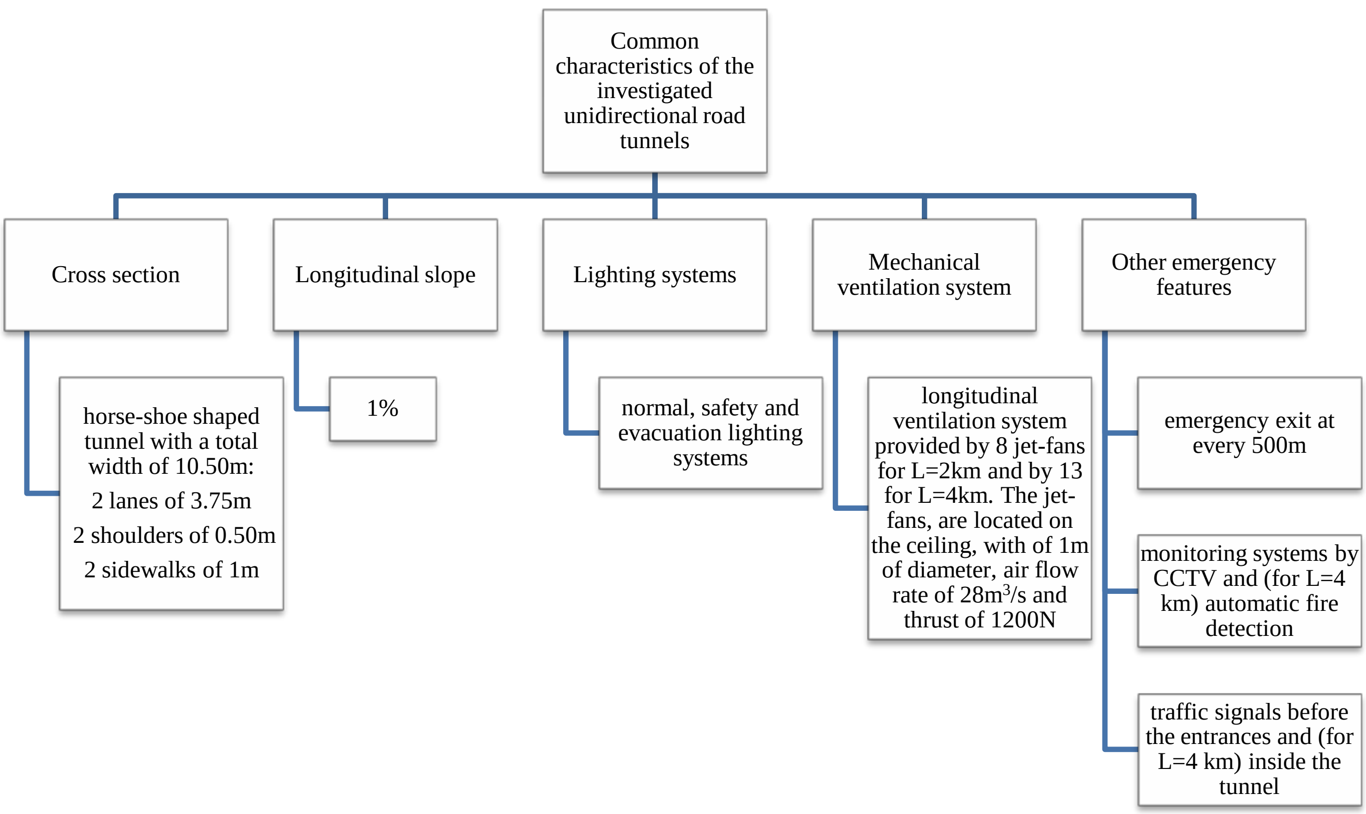

Fig. 2 Common characteristics assumed in the present study for tunnels considered.

IV. Analysis of Results

In this paragraph the results of DG-QRAM software applications are reported as F/N curves and as expected value (EV) of risk.

A. *F/N curves*

Figure 3 shows the F/N curves obtained (reported in 4 bi-logarithm charts). One can note how the risk level is positively associated with: L, AADT per lane, percentages of HGVs and DGVs.

Furthermore, many F/N curves are contained within the ALARP. It is to be stressed that this result does not indicate a totally safe condition, but a subsequent analysis is required in order to compare the benefits to costs of possible additional safety measures in order to reduce the risk level.

A reduced number of the F/N curves were found, instead, to be beyond the threshold of intolerable risk for higher percentages of HGVs and DGVs, as a consequence additional safety measures must be implemented in these cases.

In particular, this happens for HGVs = 30% and DGVs = 24%, when L=2 km and AADT per lane = 5000 vehicles/day and when L= 4 km and AADT per lane is 5000 vehicles per day, in the cases of HGVs = 30% with DGVs= 24%. For HGVs = 20% and DGVs = 24%, the curve tends to be very close to the upper limit.

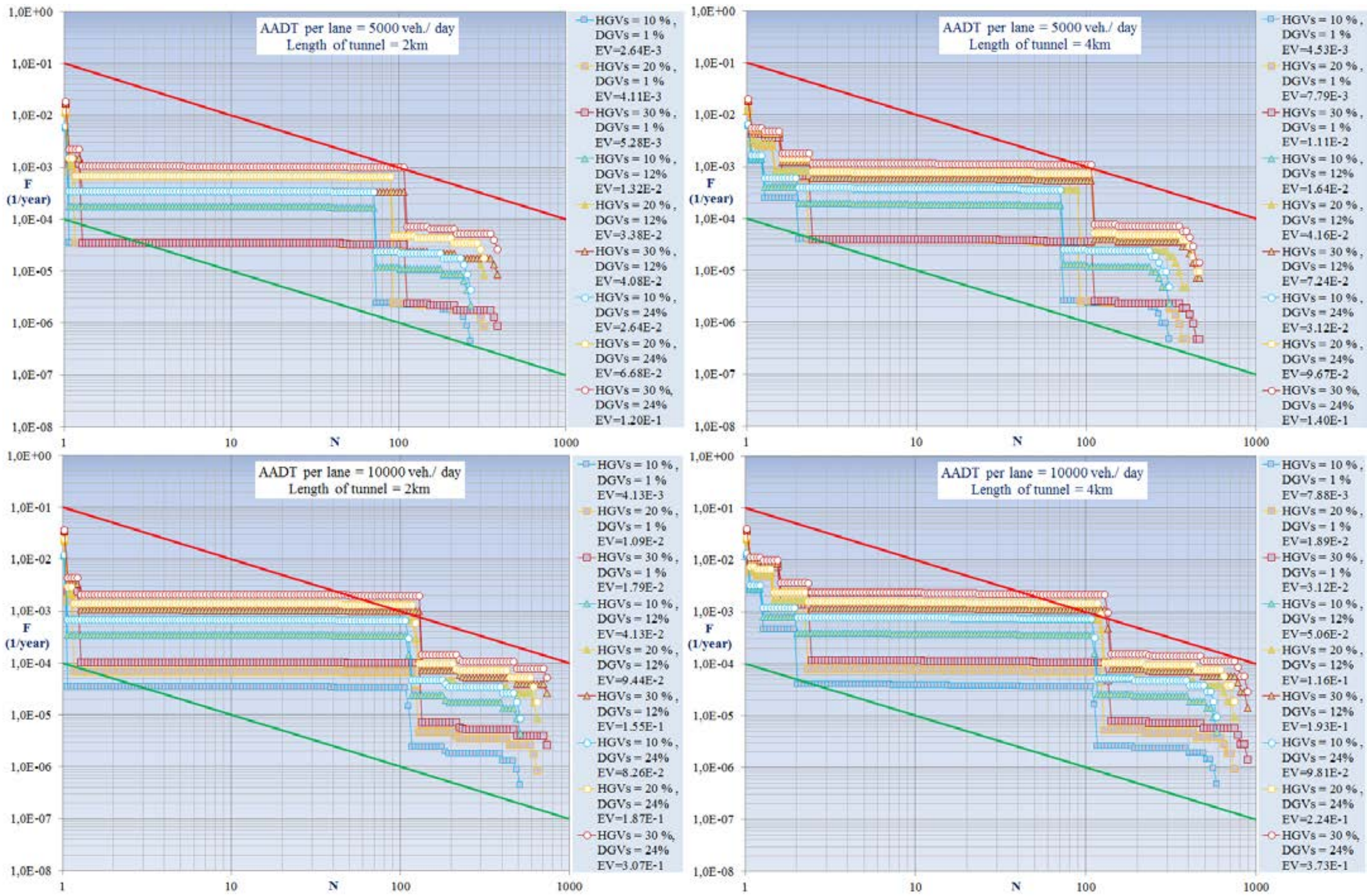

Fig. 3 F/N curves for the 36 investigated scenarios based on two types of tunnel (L=2km and L=4km) and 18 traffic conditions

When AADT per lane is equal to 10.000 vehicles per day and L= 2 km, the F/N curves are beyond the upper limit for HGVs ≥ 30% with DGVs ≥ 12%, and for HGVs ≥ 20% with DGVs ≥ 24%.

Finally, when AADT per lane is still 10.000 vehicles per day and the tunnel length is 4 km, also the F/N curve characterized by HGVs ≥ 20% with DGVs≥ 12% is above the threshold of the intolerable risk.

With the purpose to reduce the risk level when the F/N curves are beyond the safety limit, among low-costs measures also traffic control strategies might be desirable.

In this respect, the tunnel management agencies (TMAs) might allow the passage of certain dangerous goods through tunnels only by night and/or under escort. In alternative a route running completely in the open air could be considered. However, in this last case should be verified the risk level of the exposed population more especially if we are in a heavily populated area.

B. *Expected values (EV) of risk*

Figure 4 shows, by means of a radar chart, the values of EV corresponding to the 36 combinations of AADT per lane, tunnel length (L), and percentage both of heavy goods vehicles (HGVs) and dangerous goods vehicles (DGVs) which were investigated.

It is possible to note that each one of the four equal parts of the graph is to represent constant values both of AADT per lane and L. Moreover, each quarter is characterized by the three different percentages of HGVs (10, 20 and 30%). In the inner part, instead, are shown graphically in different colours the three surfaces corresponding to the values of EV computed for DGVs equal to 1, 12, and 24 % respectively.

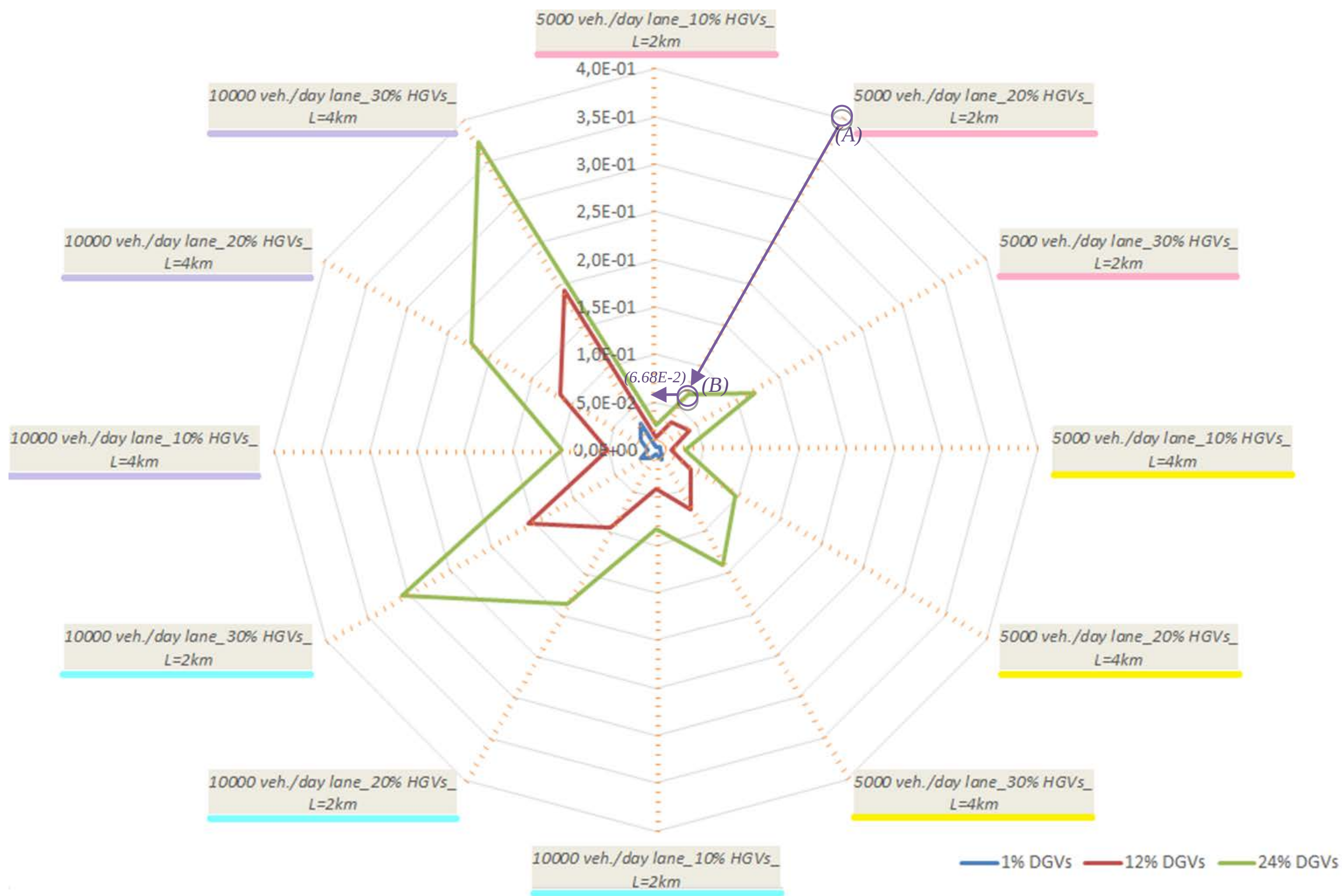

Fig. 4 Radar chart for a comprehensive representation of all values of risk

As an example, for AADT per lane equal to 5000 vehicles/day with L = 2 km, and HGVs = 20% (see point A of graph), one can estimate for DGVs = 24% a value of EV = 6.0E-2 (point B).

Obviously for values of the input parameters that were not investigated in this paper, the reader can always use the aforementioned radar chart by applying linear interpolations. The radar chart proposed in this paper might be used to Tunnel Management Agencies (TMAs) for a rapid assessment of the risk level and to choice more appropriate traffic control strategies in order to reduce the risk that can be caused by the transit more especially of dangerous goods.

V. Summary and Conclusions

A quantitative risk analysis of unidirectional road tunnels, which have characteristics in compliance to Directive 2004/54/EC [6], for different combinations of the tunnel length (L), annual average daily traffic (AADT) per lane, percentages both of heavy goods vehicles (HGVs) and dangerous goods vehicles (DGVs) was performed.

The present study made use of the DG-QRAM software because of its specific skill in the analysis of risk concerning the transport of dangerous goods through road tunnels.

The results, expressed in terms of social risk (as F/N curves) and expected value EV, showed that the risk level is positively associated with: L, AADT per lane, percentages of HGVs and DGVs.

Furthermore, many F/N curves were within the ALARP region, as a consequence a subsequent analysis based on cost-benefit analysis was required in order to understand if additional safety measures for reducing the risk level should be made.

Finally, certain F/N curves were found to be beyond the threshold of intolerable risk for higher percentages of HGVs and DGVs; as a result, additional safety measures must be implemented.

A radar chart was also proposed in order to help Tunnel Management Agencies (TMAs) in making more appropriate decisions in traffic control strategies regarding more especially DGVs.

In the light of the applications of the DG-QRAM software, with its strengths and weaknesses, that leaves the risk analyst with the responsibility of accounting for the effects of certain parameters that cannot modelled in analysis, according to the authors of the present paper further studies should be addressed to making developments additional possible.

In this respect, it is to be said that in Technical Committee PIARC TC D5-Road Tunnel Operations is now active a task group for updating the aforementioned software.

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