SIMPLIFIED METHOD FOR RISK EVALUATION IN UNIDIRECTIONAL ROAD TUNNELS RELATED TO DANGEROUS GOODS VEHICLES

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ABSTRACT

A simplified method for estimating the risk level in unidirectional road tunnels is presented in this paper. It provides the estimation of the risk level, expressed in terms of the expected value $EV$, as a function of the tunnel length ($L$), the annual average daily traffic per lane (AADT), the percentage both of heavy goods vehicles (HGVs) and dangerous goods vehicles (DGVs).

The method proposed might support Tunnels Management Agencies (TMAs) in making more appropriate decisions about the strategies of traffic control when the risk due to peak hours of traffic volume, including more especially dangerous goods vehicles, is considered to be excessive compared to normal standards of safety in tunnels.

In this respect, in order to reduce the risk level, TMAs could permit the transit of dangerous goods vehicles through tunnel by night, and/or under escort, or an alternative route running completely in open air could be tested.

Key word: Simplified method, Risk analysis, Road tunnels, Dangerous good vehicles.

Cite this Article: Ciro Caliendo and Maria Luisa Guglielmo, Simplified Method For Risk Evaluation In Unidirectional Road Tunnels Related To Dangerous Goods Vehicles, International Journal of Civil Engineering and Technology, 8(6), 2017, pp. 960–968.

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1. INTRODUCTION

The free movement of goods on European roads is a crucial factor in the development of markets in European countries and the volume of freight, carried on Europe’s roads, increases continuously [1. For giving a quantitative idea, about 39 million freight vehicles circulating on the roads of the EU-28 at the end of 2013 has been estimated, with a rate of 77.8 utility vehicles per 1000 inhabitants.


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Among the freight vehicles, dangerous goods vehicles (DGVs) have a relevant importance for safety both on roads and within tunnels. Their circulation is governed, from 1957, by European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) [2]. In the light of this agreement, each Contracting Party can apply restrictions to the passage of vehicles carrying dangerous goods through tunnels. This is made by means of assigning a specific category to each tunnel: from A (no restriction) to E (all dangerous goods are prohibited). The tunnel category, which is based on the consideration that in tunnels the severe accidents can be caused by explosion, release of toxic gas (or volatile toxic liquid) and fire, must be made by each country competent authority. However, many countries (e.g., including also Italy) have great difficulty to apply these restrictions due to geographical characteristics, political and/or social implications, as well as for management problems of tunnels belonging to border roads. Therefore, in lack of the specified category, a tunnel has to be considered free to the transit also of dangerous goods vehicles (DGVs). This means that the legal responsibility of the circulation of DGVs is attributed to the Tunnel Management Agency (TMA). For this reason, TMAs need tools for making more appropriate decisions about to limit or forbid that DGVs pass through a tunnel.

In this respect, a quantitative risk analysis (QRA) was chosen to be suitable by Italian Ministry of Infrastructure and Transports [3], in adopting the Directive 54/EC [4] published in 2004 (after the catastrophic tunnel fires that occurred in the early 2000s). In this Directive, with the aim to identify European safety standards for road tunnels, the minimum safety requirements are reported, and moreover it is specified when tunnels are opened to dangerous goods that a risk analysis should be carried out in order to establish if additional safety measures should be implemented.

Most part of risk analyses are based on an average value of the percentage DGVs. Indeed, dangerous goods flow is not constant but can vary depending on the type of road containing the tunnel investigated or during day peaks of dangerous goods volumes might be expected. Therefore, in some cases, making a risk analysis of tunnel based only on the average value of DGVs might be not justified. In the light of the aforementioned considerations, taking into account the variability of the DGVs traffic flow is within the scope of this paper.

Different risk analysis models are used in various countries (see [5] for a summary). In Europe, for the risk analysis of DGVs only (i.e., it is not strictly 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 [6].

Applications of the risk analysis can be found in: Ronchi et al. [7], Zulauf [8], Zhou et al. [9], Knofflacher and Plaffenbichler [10], Petelin et al.[11], Kyriotopoulos et al. [12], Steiger et al. [13], Saccamanno and Haastrup [14], Hall et al. [15], Parson Brincherh off Quade & Douglas [16], Diernhofer et al. [17], Benekos and Diamantidis [18], and recently Caliendo and De Guglielmo [19] and [20].

In particular with reference to Italian studies, in [19] a quantitative risk analysis (QRA) applied to a bidirectional road tunnel was carried out for different combinations of hourly traffic volume (VHP) and percentage of heavy goods vehicles (HGVs). In [20] the QRA was extended to the evaluation of the risk level in bidirectional road tunnels due to the transit of dangerous goods vehicle (DGVs). Moreover, a comparison with an alternative route running completely in open air was also made. However, it is to be said that in [19] and [20] unidirectional road tunnels were not investigated, which is another objective of this paper.

Tunnel Management Agencies (TMAs) need often to make decisions on more appropriate strategies of traffic control when is expected that the risk level due to the variability of traffic,
during day and/or week, might achieve the threshold of the intolerable risk. This might happen, for instance, more especially during the peak hours of the transit of DGVs. In this respect, a simplified method for rapidly estimating the risk level as a function of both the tunnel geometry and the entity and composition of traffic might support the TMAs.

Traffic demand can vary by day of the week and/or by hour of the day also in other given road locations, for instance more especially at road intersections where if the capacity is insufficient to meet the demand bottlenecks are expected. Also in these cases Road Management Agencies (RMAs) need methods that support them in making rapid decision on traffic control in order to avoid the congestion. On the performance of road intersections, which is not within the scope of this paper, certain references can be found, for example, in [21] and [22].

As a result of above, there are at least three main reasons for justifying this paper. The first is motivated by the need to quantify the effects on the risk level in road tunnels due to the increasing flow of DGVs. The second is to have a better understanding about the risk level in unidirectional tunnels that are in compliance with the Directive 54/EC. Finally, given the lacuna regarding simplified methods of risk, design charts that had not been developed before to support rapidly the TMAs in the decision process should be proposed.

The present paper is organized as follows: the next section contains the description of the general concept of quantitative risk analysis; while the subsequent sections deal shortly with the software used and the characteristics of unidirectional tunnels investigated. Then the results are presented and discussed and a simplified method for estimating the expected value (EV) of risk is proposed. Finally the conclusions and addresses for further studies are made.

2. QUANTITATIVE RISK ANALYSIS

2.1. General concepts

Generally speaking, two main groups of approaches appertain to the quantitative risk analysis (QRA), which are deterministic and probabilistic, respectively. However the probabilistic method compared to the deterministic one, which can give accurate results only if the exact input parameters are known, is generally considered to be the best tool. In fact it takes into account the uncertainty associated with some parameters describing the process and assesses long-term risk in more complex systems as 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.

Furthermore, two suitable approaches for the risk assessment are also possible: a scenario-based approach, which is based on a risk assessment for each individual scenario that is evaluated to be relevant; a system-based approach, able to investigate an overall system in an integrated process with aim to obtained risk value for whole system.

According to these distinctions, the QRA used in this paper has a probabilistic and system-based approach. The results are considered in terms of social risk (e.g., the expected number of fatalities in the tunnel per year). In particular, if F(N) denotes the frequency [1/year] of an event that causes N or more victims (in terms of number of fatalities), the social risk (SR) can be defined as follows: SR=F(N)•N. The social risk has: i) a graphic representation by means of F/N curves in a bi-logarithmic chart; ii) a numerical value, the expected value of risk or EV, that can be calculated as integral between 1 and the Concerning the thresholds of risk level, it has to be said that, according to the Directive 2004/54/EC, each single Member State had to define its own limits for the evaluation of results. The Italian Ministry of Infrastructure and Transports [3] has maximum possible number of victims N in a certain time period:
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 (as low as reasonably practicable) region is individualized 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 by their costs. When the $F/N$ curve lies below the threshold of the tolerable risk, additional safety measures are not necessary. When the $F/N$ curve is within the ALARP area, the implementation of additional safety measures should be justified by a cost-benefit analysis. However, it is to stressed that in order to save space in this paper we will comment only on the results expressed in terms of EV.

2.2. Software description

The software, identified as useful for the purpose of this study, is the above mentioned DG-QRAM. It considers only 13 accident scenarios since a comprehensive assessment of the quantitative risk analysis, on the transport of goods through tunnels, needs simplifications. Two scenarios are concerning fire due to heavy goods vehicles with no dangerous goods characterized by HRR (heat release rate) of 20 and 100 MW, for a benchmark only; while the remaining scenarios consider fires, explosions or releases due to heavy vehicles carrying tank, bulk or cylinders of: liquefied petroleum gas (LPG), motor spirit, chlorine, ammonia, acrolein, liquefied refrigerated CO$_2$. DG-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: geometry, traffic, ventilation system, drainage, emergency escape, density of population, etc. The results for each scenario can be reported both in terms of social risk by means of $F/N$ curves and also in term of expected value (EV).

3. STUDIED TUNNELS

Two types of unidirectional road tunnels at design stage, called in the following type I and type II, are analyzed in this paper. The types of tunnels are based on two key parameters: annual average daily traffic (AADT) per lane and tunnel length (L). Furthermore, these tunnels are supposed satisfying the EU minimum safety requirements (reported in EU Directive, and with additional details in the Italian Decree). Figure 1 shows the cross section regarding the tunnels investigated.
Table 1 Tunnels description according to EU Directive 2004/54 with traffic per lane over 2000 veh./day.

<table>
<thead>
<tr>
<th>Length</th>
<th>Type I</th>
<th>Length</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 &lt; L ≤ 3000 m</td>
<td></td>
<td>L &gt; 3000 m</td>
<td></td>
</tr>
<tr>
<td>Tunnel categories</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AADT per lane</td>
<td>5000 veh./day and 10,000 veh./day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage of HGVs</td>
<td>20% and 30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage of DG-HGVs</td>
<td>1%, 6%, 12%, 18% and 24%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal slope</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency exits</td>
<td>At every 500 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting systems</td>
<td>Normal, safety, and evacuation lighting systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal ventilation system</td>
<td>Provides by 8 jet fans on the ceiling with 1 m of diameter, air flow rate of 28 m³/s and thrust of 1200 N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring systems</td>
<td>CCTV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic signals</td>
<td>Before the entrances</td>
<td></td>
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</tbody>
</table>

Type I and type II indicate, as synthesized in the previous Table 1, two categories of tunnels widespread foreseen on Italian rural roads: length greater than 1 km, two lanes, no emergency lane, and traffic per lane of 5000 and 10,000 veh./day, respectively.

For these tunnels, two percentages of heavy goods vehicles (HGVs) are considered: 20 and 30%. In addition, table 1 also shows the percentages of vehicles transporting dangerous goods (DGVs) as part of heavy goods vehicles (HGVs).

By starting from an average value in Italy (as reported in ANFIA-ACI, 2013) equal to 1% of DGVs, we evaluated the impact on the risk level in the aforementioned tunnels for the following other different percentages of DGVs: 6%, 12%, 18%, and 24%.

4. ANALYSIS OF RESULTS

The results of DG-QRAM applications are reported for the above described two types of tunnels: L = 2 km and L = 4 km, respectively, with AADT of 5000 and 10,000 veh./day per lane and for the two different percentage of heavy goods vehicles (%HGVs = 20% and 30%, respectively), as a function of the percentage of dangerous goods vehicles (% DGVs = 1, 6, 16, 18, and 24%)

Figure 2 shows the results obtained in terms of the expected value of risk (EV) as a function of the percentage of DGVs with reference to AADT per lane equal to 5000 veh/day (similar results were obtained for AADT per lane of 10,000 veh/day, which are omitted to save space).

It is interesting to note that the risk level increases in a linear way with the percentage of DGVs. However, when the percentage of HGVs is higher (e.g. by passing from 20 to 30%) the risk level increases more rapidly with DGVs (i.e. a higher gradient was found).
It can also synthetically be added that, in almost all the cases investigated, the FN curves were contained within the ALARP region, except for the maximum value of the percentage of DGVs examined (24%) with the corresponding F/N curve that touches or partially is beyond the Italian upper ALARP limit (i.e., risk intolerable threshold). Therefore, safety measures must be implemented only when the percentage of DGVs is equal or greater than 24%; while with the DGVs less than 24% the implementation of additional safety measures should be justified by a cost-benefit analysis.

4.2. Simplified method to assess the risk level
All results obtained were organized in order to develop a simplified method in which the risk level expressed in terms of EV can be estimated in a short time as a function of: tunnel length (L), annual average daily traffic per lane (AADT), percentage of heavy goods vehicles (HGVs) and percentage of dangerous goods vehicles (DGVs). In particular, a radar chart is proposed as reported in Figure 3 of this paper. This might be used by 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 peak hours of traffic, more especially of dangerous goods vehicles.

**Figure 2** EV values for the different percentages of DG-HGVs and AADT= 5000 veh./day per lane
Figure 3 Radar chart for a comprehensive representation of all values of risk.

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 length. 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 colors the three surfaces corresponding to the values of EV computed for DGVs equal to 1, 12, and 24% respectively. 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.

4. CONCLUSIONS

A simplified method for estimating the risk level in unidirectional road tunnels, which have characteristics in compliance with the European Directive 2004/54/EC, is presented in this paper.

The results, expressed in terms of the expected value (EV) of risk, show how the risk level is positively associated with the tunnel length (L), the annual average daily traffic per lane (AADT), the percentage of both heavy goods vehicles (HGVs) and dangerous goods vehicles (DGVs).

The method developed can help Tunnels Management Agencies (TMAs) in making more appropriate decisions, and in short time, regarding the strategies of traffic control before that the risk due to peak hours of traffic volume, including more especially dangerous goods vehicles, can achieve the threshold of the intolerable risk. In this respect in order to reduce the risk level, TMAs might implement low-cost safety measures. For instance TMAs could permit the transit of DGVs and/or HGVs through tunnel by night, and/or under escort, or an alternative route running completely in open air could be foreseen.

However, it is to be said that some provisions of the Directive, cannot be modeled in the current version of the DG-QRAM. This leaves the risk analyst with the responsibility of accounting for the potential effects of the parameters that cannot be modeled in risk analysis.
Concerning these weaknesses of the DG-QRAM, recently in the Technical Committee TC-D5 Road tunnel Operation of PIARC is now active a task group for updating the mentioned software. Therefore many studies in this direction should be made for making developments possible in the field of risk in road engineering.

REFERENCES


