Quantitative Risk Assessment of Heavy Goods Vehicle Transport through Tunnels - the Tauerntunnel Case Study

H. Knoflacher, P. C. Pfaffenbichler, H. Nussbaumer
Institute for Transport Planning and Traffic Engineering
Vienna University of Technology
Gußhausstraße 30/231, A-1040 Wien

ABSTRACT
This paper has two principle objectives. The first is to present the concept of quantitative risk assessment. The second is to assess the risk reduction potential of proposed mitigation measures. A definition of risk and how to measure it is given. A quantitative risk assessment software, developed in an international research project, is presented. One of its purposes is to calculate the effects of mitigation measures. Following a series of catastrophic events in European road tunnels several measures were proposed by experts and politicians. The assessment results for two of them are shown here. The Tauerntunnel was selected as case study. The first measure which is already in action is an improved emergency ventilation. The second measure which is proposed by French authorities for the Mont Blanc tunnel is forcing heavy goods vehicles to stay 150 meter clear from vehicles in front of them. The QRA calculations show that both measures have significant potential to reduce the risk caused by heavy goods vehicles in tunnels.
Key words: societal risk, dangerous goods, emergency ventilation, mitigation measures

1. INTRODUCTION

The work presented here was mainly carried out as part of the research project "Transport of Dangerous Goods Through Road Tunnels (ERS2)". ERS2 was part of "The Road Transport and Intermodal Linkages Research Programme (RTR)" by OECD (Organisation for Economic Co-operation and Development). The following countries and organisations participated in the project: Australia, Austria, Belgium, Denmark, France (Chair), Italy, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, United States, World Road Association (PIARC) and European Commission. Within the task "Methodologies relating to risk assessment and decision process" two software products were developed: a "Quantitative Risk Assessment (QRA) Model" and a "Decision Support Model (DSM)". Subject of this paper is the QRA model. It was developed by a consortium of consultants from France, England and Canada. The model calculates the risk caused by road traffic with heavy goods vehicles (HGV). A special focus was laid on the transportation of dangerous goods (DG). During the period 1999 to 2001 the QRA software was validated based on data from existing tunnels in Austria, France, Netherlands, Norway, Sweden and Switzerland. The Institute for Transport Planning and Traffic Engineering was chairing the validation group. The following chapter 2 gives a brief overview about the basics of the QRA model. In chapter 3 the application of the QRA software to an Austrian case study is shown.

2. THE QUANTITATIVE RISK ASSESSMENT MODEL

Risk is defined by two aspects: the occurrence probability of an event and the consequences of an occurring event. A common way to describe societal risk is to calculate F/N curves. F/N curves illustrate the relationship between accident frequency and accident severity. On the abscissa the number of victims x (fatalities, injured people or both) is shown in logarithmic scale. On the ordinate the corresponding yearly frequencies F(x) for the occurrence of accidents with x victims are shown (also in logarithmic scale). For each given situation (population, traffic, DG traffic, route, weather, etc.) one F/N curve represents the societal risk. Figure 1 gives an example for an F/N curve.

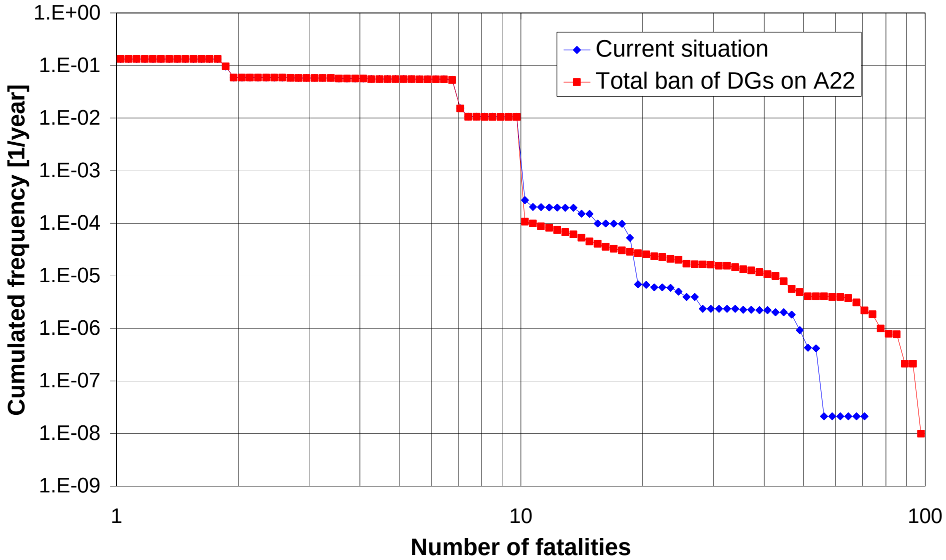

Figure 1: Example F/N curve (Knoflacher, Pfaffenbichler, 2001)

A complete assessment of risks caused by transport of DGs would require the consideration of all kinds of dangerous materials, all meteorological conditions, all accidents, sizes of breaches, vehicles fully or partially loaded etc. As the coverage of all circumstances is impossible, simplifications have to be made. The QRA model developed by the OECD is based on the following steps:

1. Choose a relative small but representative number of goods;
2. Select a relative small but representative number of accident scenarios involving these goods;
3. Determine the physical effects of these scenarios (for open road and tunnel sections);
4. Determine the physiological effects of these scenarios on road users and local population (fatalities and injuries);
5. Take into account the chance to escape and/or shelter
6. Take into account different risk reduction measures and
7. Determine the associated probabilities of occurrence.

Table 1 shows which scenarios were selected as representative in the QRA model. Two scenarios are relating to fires of medium and high intensity involving HGVs without DG. These scenarios represent a quite serious risk in tunnels. The other scenarios involve dangerous goods loading. The DGs are selected to represent various groupings of dangerous goods. They have been chosen to examine different severe effects: overpressure, thermal effect and toxicity.

Table 1: Main characteristics of the 13 scenarios modeled in the QRA

Scenario No.	Description	Capacity of tank	Size of breach (mm)	Mass flow rate (kg/s)
1	HGV fire 20 MW	-	-	
2	HGV fire 100 MW	-	-	
3	Boiling liquid expanding vapour explosion (BLEVE) of liquefied petroleum gas (LPG) in cylinder	50 kg	-	
4	Motor spirit pool fire	28 tonnes	100	20.6
5	Vapour cloud explosion (VCE) of motor spirit	28 tonnes	100	20.6
6	Chlorine release	20 tonnes	50	45
7	BLEVE of LPG in bulk	18 tonnes	-	
8	VCE of LPG in bulk	18 tonnes	50	36
9	Torch fire of LPG in bulk	18 tonnes	50	36
10	Ammonia release	20 tonnes	50	36
11	Toxic liquid (Acrolein)	30 000 l	50	24.8
12	Toxic liquid	100 l	4	0.02
13	BLEVE without thermal effects	20 tonnes	-	-

Key: BLEVE = Boiling liquid expanding vapour explosion; LPG = Liquid petroleum gas; VCE = Vapour cloud explosion
Source: (OECD, 2001)

3. THE TAUERNTUNNEL CASE STUDY

3.1. Background

The Tauerntunnel is a 6,401 meter long, rural, drilled, one bore tunnel with transverse ventilation. The tunnel is situated on the north-south-bound highway A10 which is an important route through the alps. The Tauerntunnel was already used as a case study in the QRA model validation. Therefore a broad database was already available. When the final version of the QRA software was available it was decided to perform an updated QRA for the Tauerntunnel. Two aspects were of special interests:

- In the aftermath of the 29th May 1999 Tauerntunnel catastrophe the air ventilation system had been modified. QRA runs were made to assess the effects of these changes.
- In the reopened Mont Blanc tunnel HGVs will have to stay clear 150 meters from vehicles in front of them. The potential effect of this mitigation measure is also assessed with the QRA software.

3.2. Traffic related data

For the use in the QRA model the average daily traffic of about 13,300 vehicles per day was sub-divided into three periods (Table 2). The speed limit is 80 km/h for all types of vehicles. Vehicle occupancy is assumed with 1.4 persons for light vehicles, 1.1 persons for HGVs and 40 persons for busses. The accident rate is $0.129*10^{-6}$ accidents per vehicle kilometers (Source: KfV). The QRA model defines five accident locations. In the standard setting the locations are distributed evenly. The expert user interface allows to change the distances. To reflect the circumstance of a higher accident rate near the portals, accident locations have been changed to 150; 180; 3,200; 6,221 and 6,251 meters. The time to stop oncoming traffic is estimated with one minute. Evacuation average speed is assumed with 0.5 m/s.

Table 2: Traffic data

Period	Time	Veh/h	HGVs	Busses	DGs/h
Peak	11:00-19:00	795	22 %	2 %	3.12
Normal	5:00-11:00; 19:00-22:00	556	17 %	2 %	1.69
Quiet	22:00-5:00	261	30 %	1 %	1.40

Source: (bmvit, 2001), information by telephone Mr. Santner, Tunnelwarte Tauerntunnel

Table 3: Share of DGs transported on the Tauern route

Dangerous Goods	Share
Flammable liquids in bulk (motor spirit, diesel oil, ...)	53 %
Fraction of flammable liquids that can potentially lead to a VCE	23 %
Propane (flammable liquefied gases) in Cylinders	0.2 %
Propane (flammable liquefied gases) in Bulk	0.8 %
Ammonia (Toxic gases) in bulk	1 %
DG potentially leading to a large (100 MW) fire (except liquids)	16 %
Others (Potentially leading to at least a 20MW fire)	29 %

Source: Registration list DG transports Tauerntunnel (January to March 2000)

3.3. Ventilation data

The Tauerntunnel ventilation system is divided into four segments (Figure 2). Three segments are 1,500 meter long and one segment is 1,900 meter long. In the normal ventilation regime the system runs at 70% of its maximum power. 133 $m^3/s*km$ of fresh air is blown into the tunnel and 80.5 $m^3/s*km$ are extracted from the tunnel (Source: Information given by Mr. Santner). The QRA software uses a rather simple ventilation model which is based on a modified American model. The model uses a constant volume flow. Figure 3 shows how the normal ventilation is modeled.

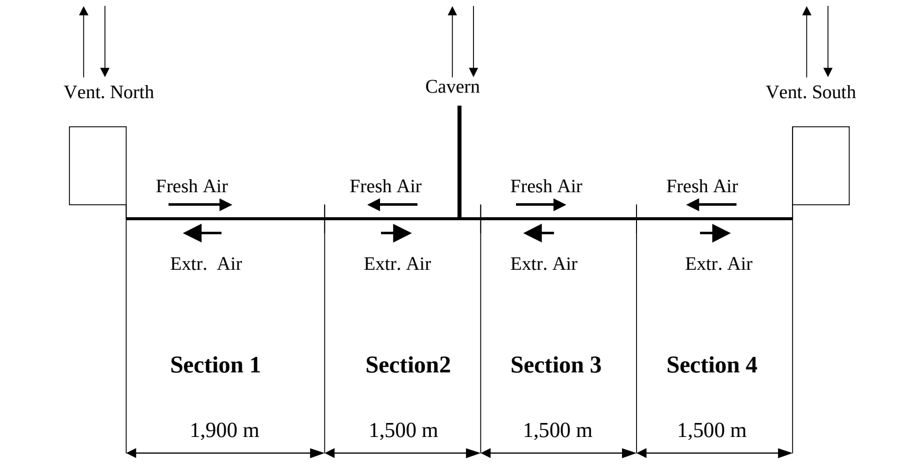

Figure 2: Outline ventilation system Tauerntunnel

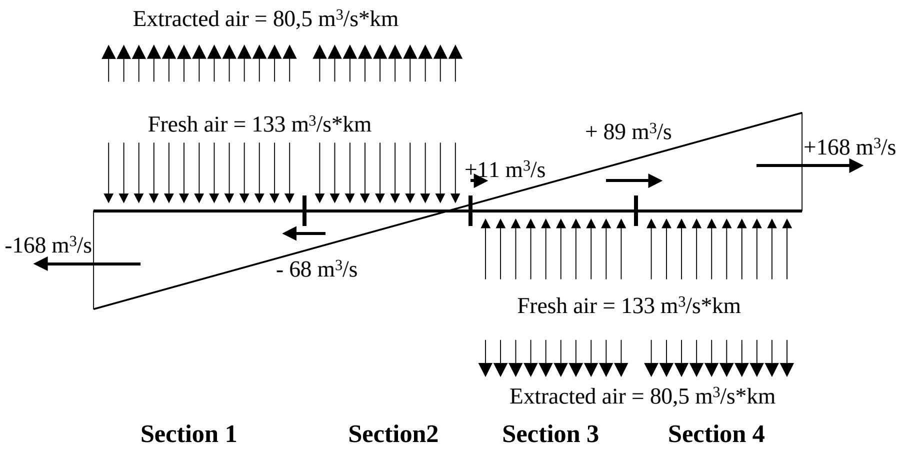

Figure 3: Normal ventilation as it is represented in the QRA model

In the old ventilation system air was extracted through slots. Figure 4 shows the way the old ventilation system is represented in the QRA model. It is assumed that the emergency ventilation needs 4 minutes to reach its full extraction flow.

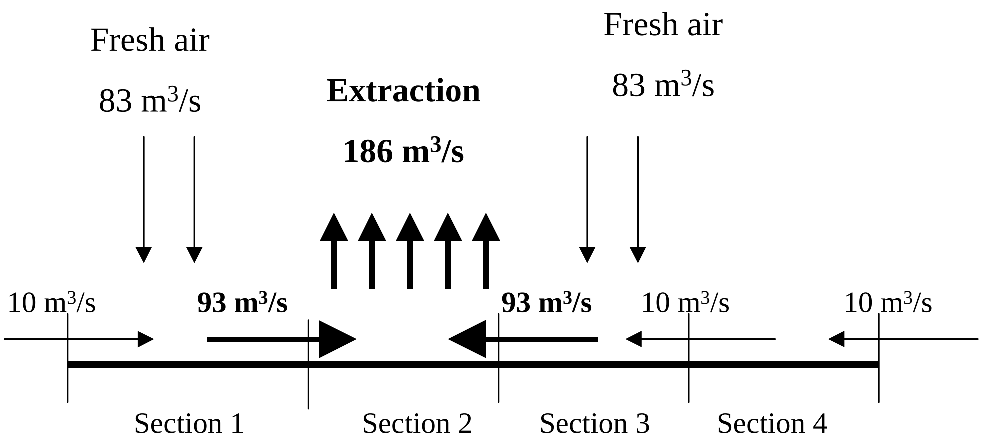

Figure 4: Modelling of the old emergency ventilation system

In the modified ventilation system there are 126 discrete openings (jalousies, every 50 m) along the whole tunnel. During normal ventilation all are opened. In cause of emergency all will be shut, except the one nearby the fire where the air will be extracted (See Figure 5). Because with the new system a smaller air mass has to be moved, it is assumed the emergency ventilation needs 2 minutes to reach its full extraction flow.

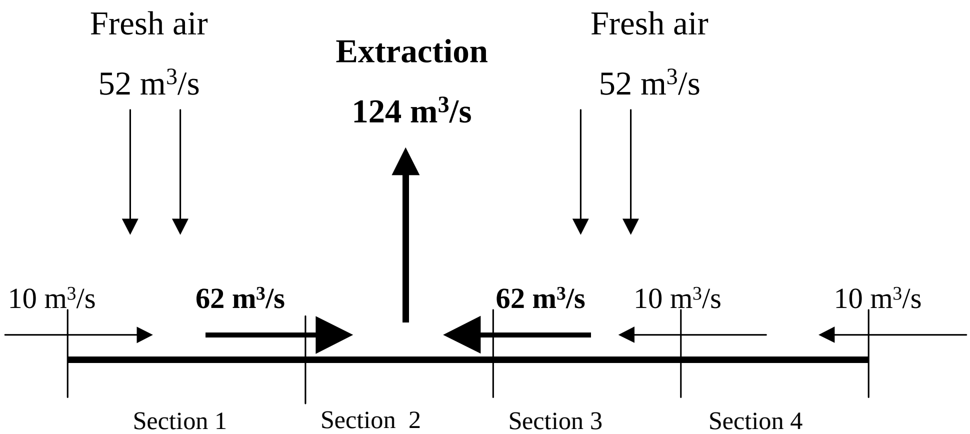

Figure 5: Modelling of the modified emergency ventilation system

3.4. Modelled mitigation scenarios

In the scenario OLD the emergency ventilation regime of the old Tauerntunnel as described in the previous chapter is used (Figure 4). In the scenario NEW 1 the modified emergency ventilation is applied as described in Figure 5. Scenario NEW 2 also uses the new emergency ventilation. Additionally it is assumed that the 150 meter distance regulation is applied. In the model this means that if the traffic stops in the case of emergency it is ensured HGVs keep a distance of 50 meters to vehicles in front. Scenario NEW 3 also uses the new emergency ventilation but additionally it is assumed that HGVs keep a 100 meter distance in emergency cases. This way to model the 150 meter distance regulation is conservative. It is not taken into account that in reality the accident ratio for HGVs would be reduced by this measure.

4. RESULTS OF THE QRA CALCULATIONS

Table 4 shows the expected values (EV) for the different event and mitigation scenarios. The expected value is the integral under the corresponding F/N-curve. The new ventilation system reduces the expected value of all scenarios involving HGVs with and without DG by about 30%. The highest reduction potential was calculated for the scenario toxic products (about 80%) while the lowest was calculated for propane in bulk (2%). The behavioral changes reduce the expected value further (all scenarios 40% to 57%). The scenarios 20-100 MW fire and flammable liquids have the highest reduction potential (40% to 57% and 46% to 64%). Again propane in bulk has the lowest reduction potential.

Table 4: Tauerntunnel Improvement of Expected Values (fatalities/year)

	OLD	NEW 1	NEW 2	NEW 3
All Scenarios	$1.428*10^{-2}$	$9.807*10^{-3}$	$5.901*10^{-3}$	$4.177*10^{-3}$
20–100 MW fires	$1.046*10^{-2}$	$7.688*10^{-3}$	$4.146*10^{-3}$	$2.766*10^{-3}$
Flammable liquids	$3.143*10^{-3}$	$1.853*10^{-3}$	$1.501*10^{-3}$	$1.175*10^{-3}$
Toxic products	$5.008*10^{-4}$	$9.367*10^{-5}$	$8.691*10^{-5}$	$7.335*10^{-5}$
Propane in bulk	$1.764*10^{-4}$	$1.728*10^{-4}$	$1.677*10^{-4}$	$1.627*10^{-4}$

F/N-curves for the different mitigation scenarios are given in Figure 6. It could be seen that the new ventilation system has its main potential for incidents with a high number of fatalities. The behavioral measure does nearly not effect the risk for incidents with high number of fatalities. The main potential of this measure is to reduce the risk for medium number of fatalities accidents.

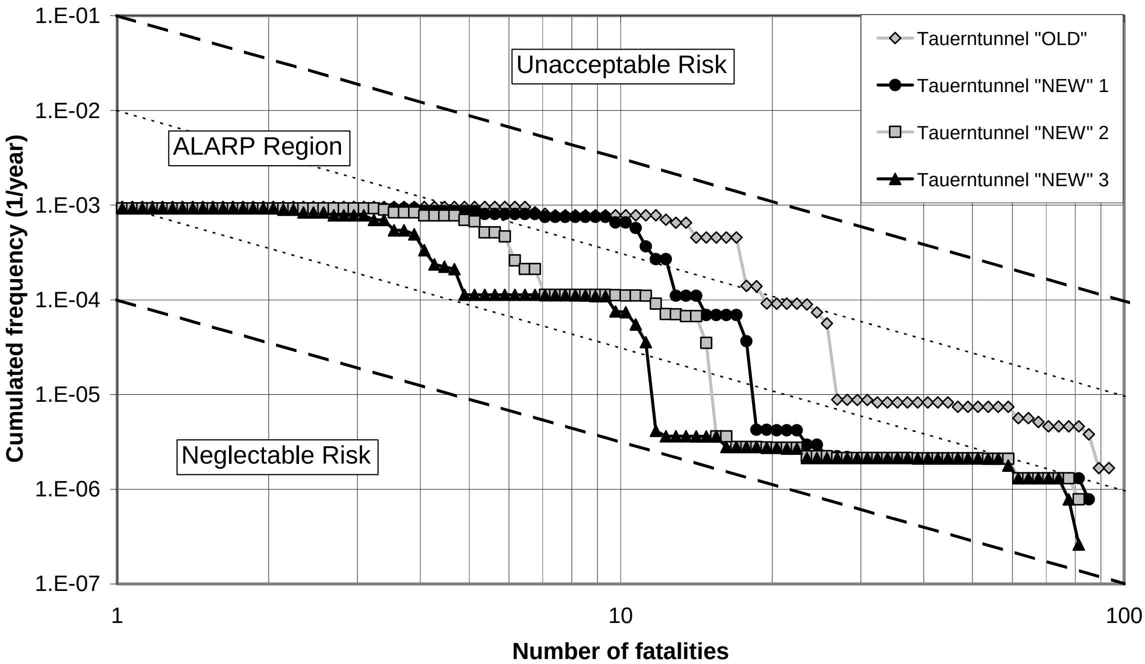

Figure 6: Results of the QRA for the different scenarios

5. CONCLUSIONS

After a series of very severe accidents in road tunnels experts and politicians proposed a huge number of measures to counteract risk of road transport through tunnels. A quantification of risk is necessary to assess the effectiveness of mitigation. The OECD project ERS2 produced a QRA model applicable to this task. This paper describes the application of QRA software to an Austrian case study - the Tauerntunnel.

Two different mitigation measures were tested: one of infrastructural and one of behavioural nature. Despite the necessary simplification the QRA modelling has proven that both measures have a significant risk reduction potential (Figure 6). The emergency ventilation improvement has its main potential in reducing risk of incidents with a high number of fatalities. Whereas the increased distance between HGVs and vehicles in front has its main potential for medium number of fatalities.

Currently there is an ongoing discussion to define an Austrian risk acceptance criteria. The thick dashed lines in Figure 6 indicate a criteria suggested by the Institute for Transport Planning and Traffic Engineering. Above the upper dashed line risk would be unacceptable. Between the two dashed lines is the so called ALARP (as low as rational possible) region. Within this area mitigation measures have to be assessed and put into action in a cost effective way. Under the lower dashed line risk could be neglected. Figure 6 shows that it was necessary to improve safety standards in the Tauerntunnel. Modifying the ventilation system went in the right direction. Nevertheless it is necessary to find further cost effective ways to reduce risk. The regulation that HGVs have to stand 150 meter off from vehicles in front could be an appropriate measure to reach this objective.

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