Risk analysis study for Slovenian motorway tunnels

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Abstract

After high-profile accidents in European tunnels in recent years, awareness of safety in tunnels increased significantly. As a result, European Parliament and Council 2004/54/EC issued a Directive on minimum safety requirements for tunnels in the trans-European network. As one of the measures introduced by Directive is mandatory preparation of risk analysis for all existing tunnels in the trans-European network. Since the Directive is limited to tunnels over 500 m long, 14 tunnels had to be investigated in Slovenia.

Under the contract with the operator, we obtain tunnel risk analysis for these 14 tunnels. The purpose of this paper is to present an integrated approach to develop risk analysis. From the legal bases, the methods of obtaining and interpreting the input data and all the results, performance measures and accompanying measures.

Due to the scale of the task we will concentrate on the two characteristical cases, namely: Tunnel Ločica and Tunnel Šentvid.

Keywords: *Tunnels, Risk Analysis, Safety in tunnels, European law*

Povzetek

Po odmevnih nesrečah v evropskih predorih, se je v zadnjih letih zavedanje o varnosti v predorih močno povečalo. Kot posledica je nastala Direktiva Evropskega parlamenta in Sveta 2004/54/ES o minimalnih varnostnih zahtevah za predore v vseevropskem omrežju. Ta kot enega izmed ukrepov uvaja tudi obvezne izdelave analize tveganj za vse obstoječe predore na vseevropskem omrežju. Ker se omejuje na predore dolžine nad 500 m, na slovenskem omrežju v ta okvir pade 14 predorov.

V okviru javnega naročila smo s strani upravljavca predorov pridobili izdelavo analiz tveganj za omenjenih 14 predorov. Namen prispevka je predstaviti celostni pristop k izdelavi analize tveganj. Od zakonskih podlag, uporabljenih metod, pridobivanja in interpretiranja vhodnih podatkov ter vse do rezultatov, ukrepov in spremljavo uspešnosti ukrepov.

Zaradi obsežnosti naloge se bomo v prispevku skoncentrirali na 2 karakteristična primera in sicer: predor Ločica in predor Šentvid.

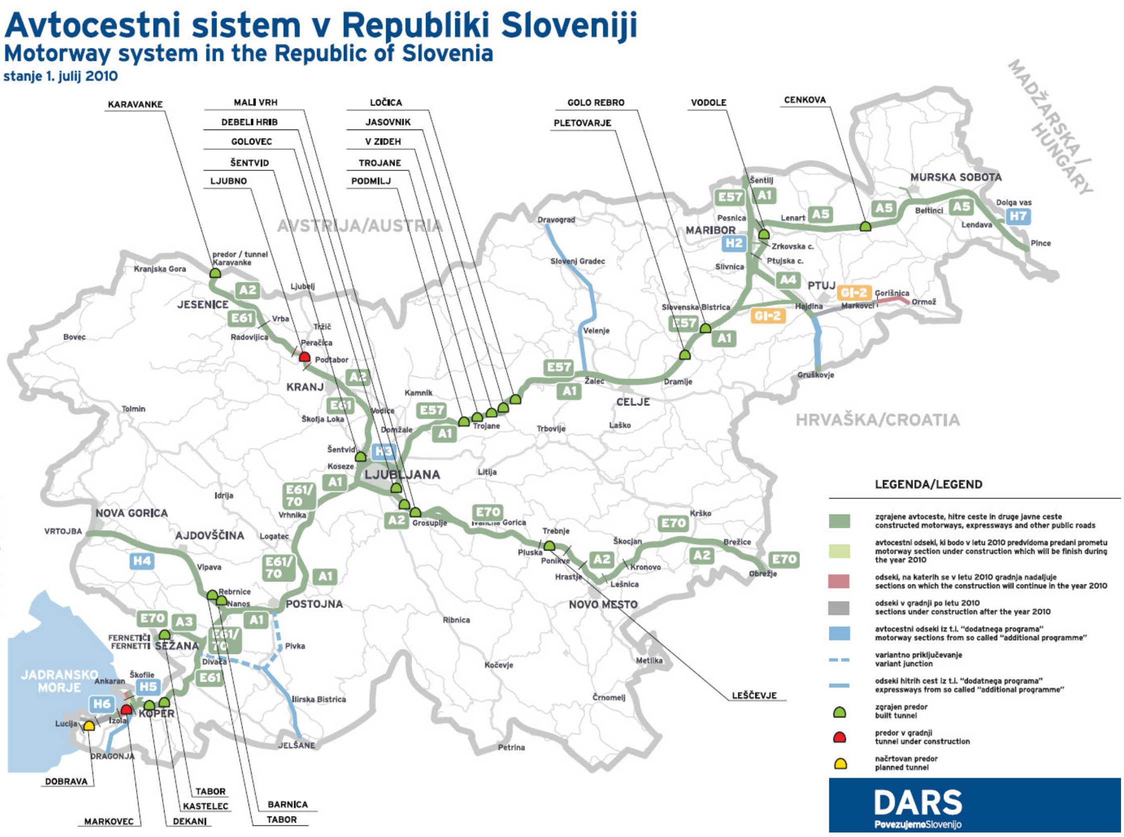
1 Scope and basis of the study

Since the beginning of the implementation of the national motorway construction program 1994 the number of tunnels in operation on the Slovenian motorway network continuously increased in the last decade. Today the Slovenian national motorway company DARS operates more than 44 tunnels in accumulated length of 36,7 km.

Nowdays DARS as a major tunnel operator soon realized that safety is one of the main aspects of operating tunnels. Parallel to that accidents with casualties evolved in nearby countries proved that increased activity in safety issues are needed.

Meanwhile on European level, Directive 2004/54/EC (the "EC-Directive") become the major legislative guideline for EU countries setting basic requirements for tunnels in the Trans-European Road Network (TERN). Folllowing that Slovenia transposed EC-Directive into Slovenian law with the Decree UL RS št. 48/2006 "Uredba o tehničnih normativih in pogojih za projektiranje cestnih predorov v Republiki Sloveniji".

Since most of the Slovenian motorway tunnels in the past were designed on the basis of the Austrian tunnelling design guidelines RVS which were also transposed into Slovenian law with the Decree UL RS št. 48/2006, hence in terms of construction and equipment they are similar to Austrian motorway tunnels. As RVS guidelines set even higher demands than EC-directive, no major differences to current practice in terms of safety was implemented with new law.



Picture 1: General view of Slovenian Motorway system with indicated existing (green), in construction (red) and in design (yellow) tunnels (source: DARS d.d.)

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The major change that EC-Directive established is an integrated approach to road tunnel safety taking all safety relevant parameters like tunnel construction, tunnel equipment, tunnel operation, traffic, vehicles and tunnel users into account.

On the one hand the EC Directive is a prescriptive guideline, defining a set of minimum requirements for the safe design, equipment and operation of road tunnels; on the other hand in some contexts the EC Directive requires decisions, based upon the results of a risk assessment process.

Therefore DARS initiated a risk analysis study to investigate all motorway tunnels in operation, in the design and in the commissioning stage with a risk based approach.

As EC directive affects only tunnels over 500 m long, DARS made a decision to first investigate all longer tunnels on motorway A1 and A2 namley Golo Rebro, Pletovarje, Jasovnik, Ločica, Trojane, Podmilj, Golovec, Kastelec, Dekani and Karavanke, in order to check current status and investigate upgrade options to improve safety. Meanwhile new tunnels such as Šentvid, Cenkova, Podnanos and others were investigated by means of risk analysis in order to comply with EC-directive procedure and to check design and execution of tunnel before they start to operate.

New tunnels are investigated in early stages of design such as Gorjanci tunnel partly to comply with EC-Directive and also to investigate different options, variants or to implement other application of risk analysis. This means that DARS was able to fully exploit the possibilities of risk analysis for different applications.

ELEA iC as tunneling engineers and ILF as global reference on field of risk assasment joint forces to tackle this demanding task.The paper will first introduce the approach and than present results from few characteristical tunnels.

2 Methodical approach

2.1 General Procedure

According to the requirements of the EC-Directive, the safety of a road tunnel is to be assessed in two different ways:

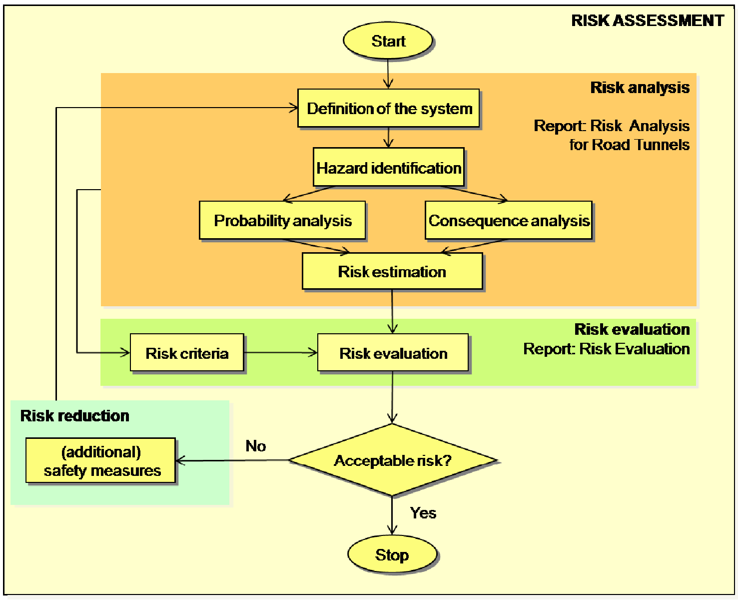
- By an approach based on prescriptive regulations:
  It must be checked, if a tunnel fulfils all applicable prescriptions of relevant guidelines

However, even if a tunnel fulfils all regulatory requirements, it has a residual risk, which has to be addressed as well; therefore the prescriptive approach is complimented.

- By a risk-based approach:
  In a systematic approach sequences and interrelations in potential incidents or accidents are analysed, hereby identifying weak points in the system and recognizing possible improvement measures (PIARC 2008, Risk Analysis for Road Tunnels).

This risk-based approach is called risk assessment. The risk assessment process consists of three key elements:

- Risk analysis: what might happen – how often, what are the consequences?
- Risk evaluation: is that risk acceptable?
- Risk reduction: which (additional) measures are necessary to get a safe tunnel?



Picture 2: Flowchart of the procedure for risk assessment (PIARC 2008, Risk Analysis for Road Tunnels).

On that basis the following procedure was established for the risk analysis study for the Slovenian motorway tunnels.

a) Specific hazard analysis:

The specific hazard analysis is the first step of the investigations; it serves to identify specific characteristics which may influence safety by analyzing the key safety parameters of the tunnel and describing their influence on the safety level in a qualitative way. Thus the relevant factors to be investigated in the risk analysis can be identified and systematic preliminary evaluations are performed quickly.

In the course of the specific hazard analysis a general inspection of the tunnel was carried out and on site interviews with operators were held in order to include practical experience in the analysis.

b) Safety evaluation on the basis of prescriptive guidelines:

All tunnels were evaluated on the basis of the Slovenian Decree UL RS št. 48. Specific aspects (such as the ventilation system) were also checked on the basis of national design guidelines; as reference guidelines the Austrian tunnel design guidelines RVS were used in most cases.

c) Quantitative risk assessment:

A quantitative risk assessment was carried out, applying the Austrian tunnel risk model TuRisMo.

d) Quantitative risk analysis for the transport of dangerous goods:

For the specific problem of DG-transport though the tunnels a separate risk analysis was carried out applying the risk model DG-QRAM.

e) Detailed analysis of specific characteristics:

In some cases a detailed analysis of specific issues was carried out, applying various approaches, supplementary to the standard investigation program.

2.2 Methods for risk assessment

In article 13 the EC Directive obliges its Member States to "ensure, that at national level, a detailed and well defined methodology corresponding to the best available practices, is used ...". When the project started in 2008, there was no established methodology for risk assessment for road tunnels in Slovenia, although there was a proposal on research basis, for a new risk analysis methodology based on establish OECD – PIARC model with additional scenario based model.

One of the first steps of the study was the selection of the most suitable risk analysis method. According to PIARC (PIARC, Technical Report 2008 R02 – Risk Analysis for Road Tunnels) none of the existing practical measures can claim to be the most suitable in practical use in all situations. For the selection of the appropriate method the specific situation of the tunnel and the issues to be investigated must be considered as well as the required depth of assessment and the available resources.

In the situation of the present study the risk analysis method

- ► must be applicable to different kinds of tunnels of different age, some with very specific problems;
- ► it must therefore be open to implement more specific, non – standard submodels, if required;
- ► it must allow for the evaluation of different kinds of risk mitigation measures;
- ► it should also be applicable for the investigation of dangerous goods transport risks.

For a comprehensive investigation of risk mitigation measures a risk model must cover all types of risk – risk due to mechanical effects of car accidents (which are the dominating share in risk in most of the tunnels) as well as risk due to various kinds of fire and due to accidents involving dangerous goods.

The investigation of dangerous goods risks is a very specific task. DG risks contribute only to a minor extent to the overall tunnel risk in terms of the expected risk value (= statistically expected fatalities per year); nevertheless, accidents involving dangerous goods need special attention because they are characterized by

- ► very small probabilities,
- ► but very high possible consequences.

Furthermore, as a big variety of different products may be involved, various kinds of scenarios may result from such accidents. Hence, for the analysis of accidents involving dangerous goods a very specific approach is required. Therefore two different risk models were chosen for the analysis:

The Austrian risk model TuRisMo was selected as standard method for the overall risk analysis for the following reasons:

- ► TuRisMo was one of the very few already approved risk analysis methods at that time.
- ► TuRisMo fulfils the demands of the EC-Directive.
- ► TuRisMo is an integrated, system-based risk model which implements almost all relevant influence parameters for tunnel safety in a quantitative way.
- ► TuRisMo was developed on the basis of Austrian experience with tunnel accidents and includes Austrian accident data; as the Slovenian tunnels were also designed on the basis of Austrian guidelines, their construction and equipment is similar to Austrian tunnels.
- ► Additionally, key parameters of the risk model can be adapted in a way that it takes the specific conditions in Slovenian road tunnels into account.
- ► TuRisMo includes all types of tunnel accidents as car accidents with mechanical effects, tunnel fires (car and HGV) and dangerous goods accidents.

However TuRisMo is not suited for an in-depth investigation of dangerous goods accidents; therefore, for this very specific topic the risk model DG-QRAM (developed by OECD/PIARC) was applied in a separate analysis.

DG-QRAM is the most commonly applied risk model for dangerous goods. It includes 13 different consequence scenarios depending on kind and amount of substances involved in an accident. Therefore DG-QRAM requires quite detailed information about the composition of products transported through a tunnel. DG-QRAM is not suited for the investigation of standard risks (like mechanical accidents and standard fires) and the options for the investigation of risk mitigation measures are quite limited.

2.3 Tunnel risk model TuRisMo

The tunnel risk model TuRisMo is an integrated quantitative risk model which was developed under the authority of the Austrian Ministry for traffic, innovation and technology together with a group of experts of different technical disciplines and published in the framework of the Austrian guidelines for road, rail and traffic RVS (RVS 09.03.11) in 2008.

The risk model allows a systematic and quantitative risk assessment taking all relevant scenarios of incidents in a road tunnel into account:

- ► Light vehicle fire / HGV fire (with/without dangerous goods) / bus fire
- ► Light vehicle accident / HGV accident (with/without dangerous goods) / Bus accident
- ► Light vehicle accident with fire – as consequence / HGV accident with fire

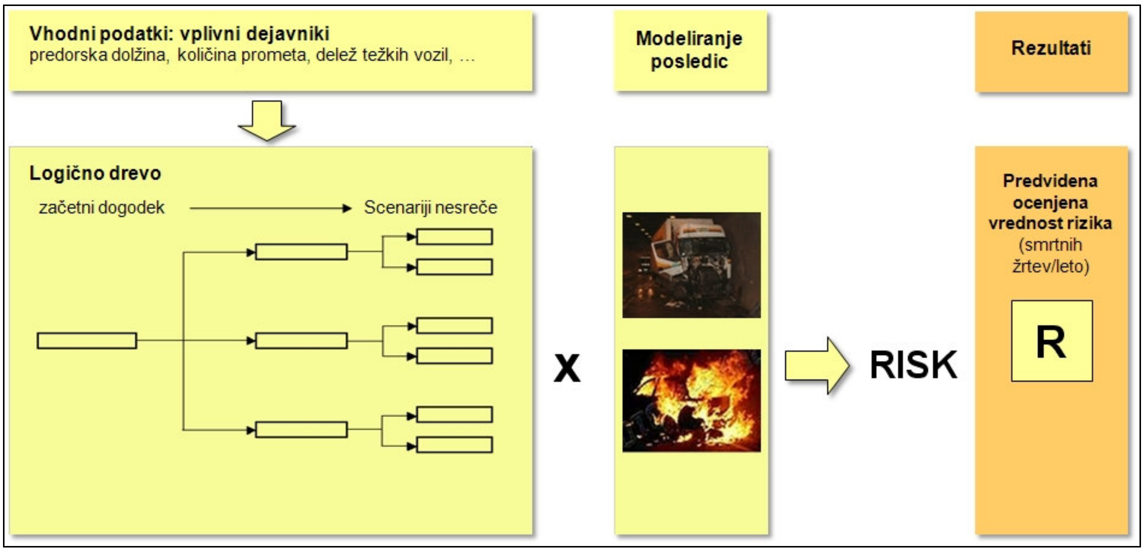
(with/without dangerous goods) – as consequence / bus accident with fire – as consequence

The risk analysis model examines the risk of tunnel users (fatalities and injuries). As reference value, the societal risk (expected value EV, statistically expected fatalities per year) of the tunnel is calculated. The share in risk of mechanical damage, fire effects and hazardous goods effects is displayed separately.

The method consists of the following two basic elements:

- a quantitative frequency analysis (event tree analysis) – to compute the frequencies of a set of damage scenarios
- a quantitative consequence analysis – assess the consequences of those damage scenarios by applying statistical approaches (mechanical accidents) and a combination of various sub models (fires)

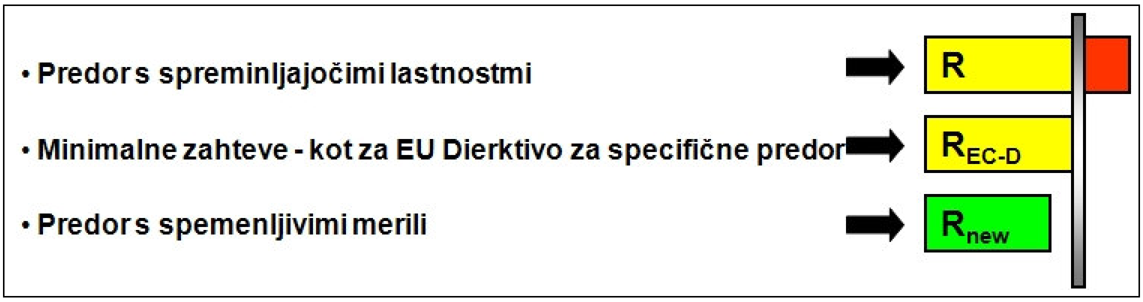
The basic structure of the tunnel risk analysis is presented in the following picture:



Picture 3: Basic structure of the risk analysis

2.4 Approach for risk evaluation

Risk evaluation is done by a relative comparison with a so called "reference tunnel". This principle of risk evaluation directly relies on the EC Directive with its safety-related minimum requirements for road tunnels: a tunnel that fulfils all requirements and conditions laid down in the EC Directive is considered as sufficiently safe. Therefore a tunnel similar to the tunnel to be investigated, which in all aspects is fully in line with the requirements and definitions of the EC Directive are defined as reference tunnel. The risk assessment is performed for both, the reference tunnel as well as the real tunnel. If the risk of the real tunnel exceeds the risk of the reference tunnel additional safety measures have to be applied to reduce the risk of the real tunnel below the risk of the reference tunnel.



Picture 4: Evaluation of results of the risk analysis

In addition to this relative approach the absolute risk values were classified according to the classification scheme of the Austrian guideline RVS 09.02.31 which can be used as a bench mark generally applicable to evaluate absolute risk level of a tunnel:

Table 1: Classification scheme for absolute risk values for tunnels on motorways – according to Austrian guideline RVS 09.02.31

Expected risk value in tunnel		**Danger classes**
lower limit	**upper limit**	
-	$2 \cdot 10^{-2}$	I
$> 2 \cdot 10^{-2}$	$1 \cdot 10^{-1}$	II
$> 1 \cdot 10^{-1}$	$5 \cdot 10^{-1}$	III
$> 5 \cdot 10^{-1}$	-	IV

The influences of additional safety measures on the risk are taken into account in the tunnel risk analysis in accordance with their effect mechanisms. With the risk model, in most cases the effectiveness of additional safety measures can be assessed in a quantitative way (referring to the expected risk value).

Thus, it is possible

- ► to verify that risk-enhancing influences can be compensated by additional safety measures and that the required safety standard can be achieved,
- ► to compare different measures or combination of measures with respect to their efficiency (in terms of risk reduction).

3 Risk analysis results

As representative examples, typical risk analysis results are presented for the following two tunnels:

- ► Tunnel Locica: as an example for a typical tunnel in operation on Slovenian motorways; most of these tunnels are undergoing an upgrading process
- ► Tunnel Šentvid: as an example for a new tunnel with specific characteristics, which was designed according to the latest generation of design guidelines.

3.1 Tunnel Ločica

3.1.1 Description of tunnel Ločica

Tunnel Ločica is one of the first tunnels built after Slovenia's independence and start of new highway construction program thus it presents a specific and also characteristic tunnel example. Specific in a way that Ločica was built in years previous to implementing new set of standard codes and guidelines (RVS and RABT) and in time when knowledge and experiences was limited among Slovenian experts.

Otherwise Ločica is typical twin tube two lane highway tunnel approx. 750 m long with typical normal profile on A1 highway section between Celje - Ljubljana. The length of the tunnel defines it as a typical middle long tunnel on the limit of implementation of ventilation, fire water system and cross passages. Nowadays it is dependant on results of risk analysis but in time of design different codes had different demands so the client decided on most rational solution.

As there is no ventilation and fire water system with only limited use of cross passage the risk analysis as presented later shows need of upgrading.

Results of the overall risk analysis for tunnel Ločica

The results of the overall risk analysis for tunnel Ločica in comparison to the respective reference tunnel are presented in table 2.

Table 2: Results of quantitative risk analysis – tunnel Ločica

	Risk/year EV[1]	**Mechanical accidents**	**Fires**	**Accidents with dangerous goods**
Ločica tunnel	0,2708	0,1783 (65,8 %)	0,0890 (32,9 %)	0,0036 (1,3 %)
Reference tunnel	0,2688	0,1830 (68,1 %)	0,0811 (30,2 %)	0,0046 (1,7 %)

[1] *long-term statistically expected number of fatalities per year*

Results of investigation of additional measures

According to the classification scheme of the Austrian guideline RVS 09.02.31 tunnel Ločica is danger class III. The main contributors to the risk of tunnel Ločica are car accidents with mechanical effects. Fire risk is about one third of the overall risk, whereas accidents with dangerous goods only contribute to a minor extent to the expected risk value.

The risk of tunnel Ločica is slightly below the risk of the reference tunnel. The risk due to mechanical accidents is higher in tunnel Ločica than in the reference tunnel. This is mainly caused by the fact that the percentage of HGV`S is higher than the respective reference value of the EC-Directive. The portion of fire risk in the overall risk of tunnel Ločica is high. This is due to the fact, that the tunnel Ločica has no mechanical ventilation system. However the short cross passage distance reduces fire risk, so that the risk level of the reference tunnel can be reached without additional risk mitigation measures.

In this context it should be mentioned that according to the regulations in the new Austrian tunnel ventilation guidelines RVS 09.02.31 as well as in the German tunnelling guidelines RABT 2006 a mechanical ventilation system would be required.

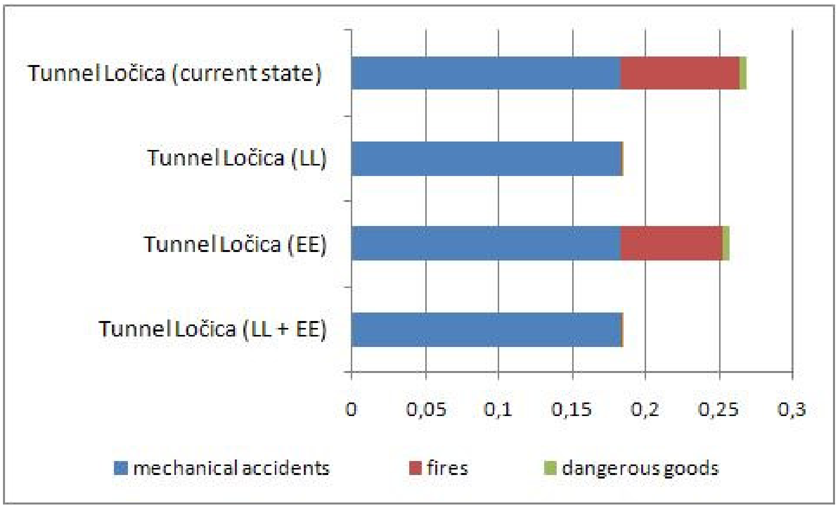
For that reason and because of the comparably high fire risk additional risk mitigation measures capable to reduce this share of risk were investigated.

The risk value of 0,2688 is a high value for a relatively short motorway tunnel.

Such measures could be

- the implementation of a mechanical ventilation system: tunnel Ločica (LL)
- a further reduction of distance of emergency exits: tunnel Ločica (EE)
- a combination of both measures: tunnel Ločica (LL + EE)

The effects of these measures on the risk of tunnel Ločica are shown in Picture 5.



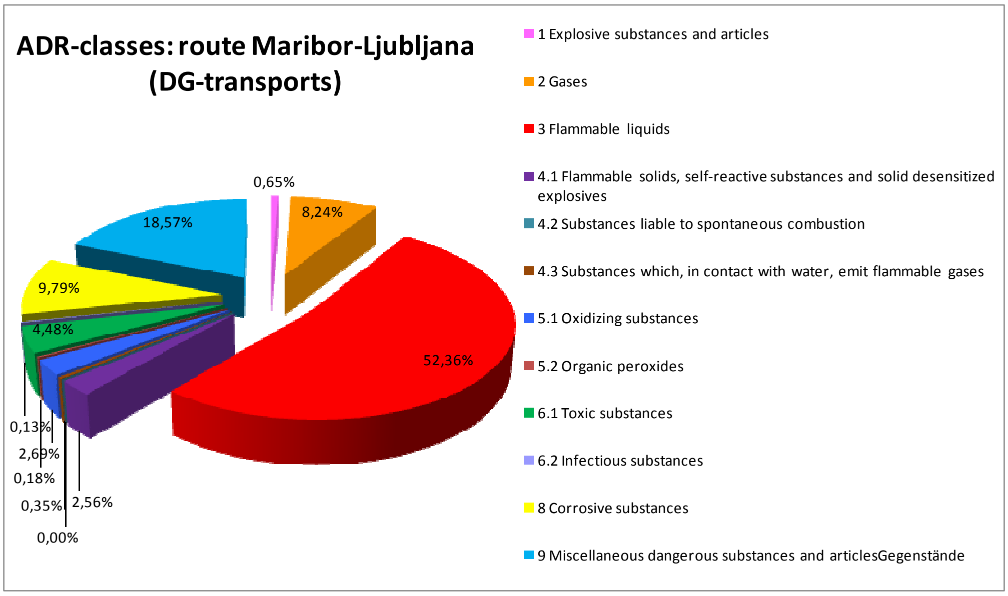
Picture 5: Results of risk analysis – additional measures

The results of the investigation of additional measures demonstrate that the overall risk can be reduced by 30 % by reducing the fire risk to a minimal value (< 1 %) by the implementation of a mechanical ventilation system. The reason is that in longitudinally ventilated tunnels with uni-directional traffic and a low frequency for traffic jams people usually are not affected by the toxic smoke from fires because of an active smoke management. Hence, longitudinal ventilation would be a very efficient additional measure to reduce fire risk in tunnel Ločica.

If two additional cross passages are built the share of fire risk could only be reduced from more than 30 % to less than 27 %. The combination of both measures can only achieve a marginal further improvement, because the ventilation nearly eliminates fire risk and then the additional cross passages are not efficient any more. Hence the implementation of longitudinal ventilation would be the preferable measure to reduce overall risk and fire risk in particular.

3.1.2 Results of the dangerous goods risk analysis for tunnel Ločica

The overall risk analysis shows that in terms of the expected risk value the dangerous goods risk is less than 2 % of the overall tunnel risk. Anyhow, risk analysis for dangerous goods was carried out applying the risk model DG-QRAM. To provide proper input to the risk model characteristic DG transport data was collected for the A1 motorway Maribor – Ljubljana (results see picture 7).



Picture 6: Dangerous goods transports on the motorway A1 Maribor – Ljubljana (ADR-classes)

The risk was calculated for the actual traffic situation as well as for the traffic data 2025.

The following results were obtained:

- Expected risk value (traffic data 2007): **EV = 1,428.10^{-3} f/year**
- Expected risk value (traffic data 2025): **EV = 4,169.10^{-3} f/year**

As example the corresponding F/N-curve for the current situation is shown in

Picture 7.

The evaluation of the results of a DG tunnel risk analysis is a very complex topic which cannot be discussed in the context of this paper. In the present study reference criteria according to the Austrian guideline RVS 09.03.12 (draft) were applied. In this guideline the following reference criteria are defined:

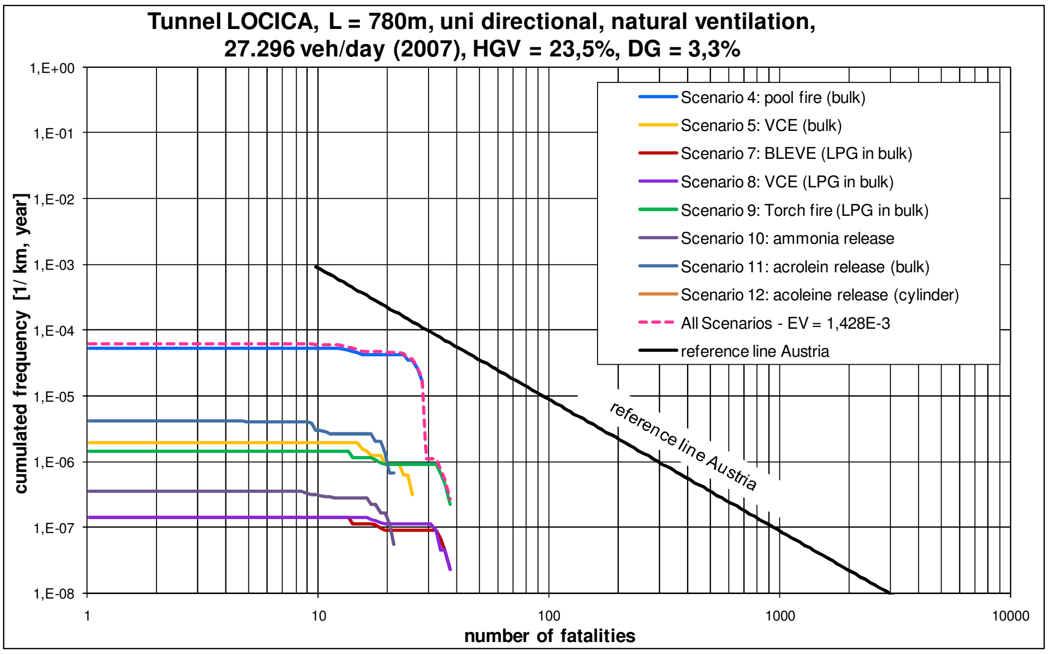
- Relevance criteria: **EV < 1.10^{-3} f/year**
- Reference line (in FN-diagram):

$$F = \frac{10^{-1}}{N^2} \times L^{0.5}$$

The expected value for DG risk in tunnel Ločica exceeds the relevance barrier of 1.10^{-3} fatalities/year in both situations (now slightly and in future clearly). This indicates that the risk is not negligible and has to be evaluated more thoroughly.

Hence the results are evaluated by comparing it to the reference line in the F-N diagram (see

Picture 7).



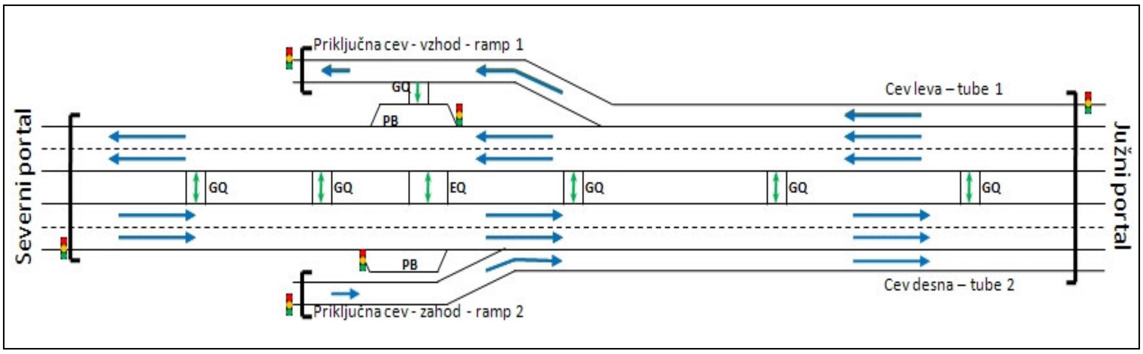
Picture 7: Resulting F/N-curves for DG risk in comparison to the reference line – current situation (2007)

The F/N-diagram in

Picture 7 shows that for the current conditions (2007) the risk of dangerous goods transports in the tunnel Ločica is acceptable. The F/N-curves of all scenarios lie below the reference line. However, in the scenario “outlook” (traffic forecast 2025) the reference line is touched. This indicates, that with increasing traffic in tunnel Ločica the DG-transport risk may reach critical values in future. Therefore the study recommends to observe the situation in the next years. Specific attention should be paid to the development of HGV traffic in general and DG-transports in particular.

3.2 Tunnel Šentvid

3.2.1 Description of tunnel Šentvid



Picture 8: System of tunnel Šentvid with emergency exits

Contrary to Ločica tunnel Šentvid presents a pinnacle of the latest technology, implementation of tunnel codes and tunnelling knowledge in Slovenia. Rather than normal tunnel it is widely described as tunnel system that started with construction over three decades ago only to be finalized with modified design in the last 7 years.

The tunnel is part of A2 section of highway between Kranj and Ljubljana in the entrance to the capital. The system consists of two main tunnel tubes with four additional ramp tunnels all concluding on the crossroad with the main northern avenue to the capital centre. Northern part of the main tunnel is a normal two lane tunnel only to widen to three lanes in bifurcation caverns where ramp tunnel enters/exits.

All the latest systems from ventilation, fire water system, management and controlling, lighting, guiding, etc…. was implemented in design and execution. The spacing between cross passages was lowered according to latest RVS recommendations to maximum 250 m which ads considerable risk reduction.

As mentioned all ramps are concluding at crossroad controlled by traffic light just after the portals. The special controlling system with multiple redundancies was implementing in order to minimise possibility of traffic jams inside the tunnel. Also as tunnel attracts around 45.000 vehicles on average per day and in peaks even 60.000 or more and with extremely busy Ljubljana Ring road in near vicinity, a complex integrated road intelligent system was implemented in way that in case of tunnel closure the traffic is transferred to possible bypasses. All this systems were included directly or indirectly in risk analysis described in later chapter.

3.2.2 Results of the overall risk analysis for tunnel Šentvid

The results of the overall risk analysis for tunnel Šentvid in comparison to the respective reference tunnel are presented in table 3.

Table 3: Results of quantitative risk analysis – tunnel Šentvid

	Risk/year EV[2]	**Mechanical accidents**	**Fires**	**Accidents with dangerous goods**
Šentvid tunnel	0,0654	0,0646 (98,7 %)	0,0002 (0,3 %)	0,0007 (1,0 %)
Reference tunnel	0,0663	0,0653 (98,5 %)	0,0005 (0,8 %)	0,0005 (0,7 %)

[2] *long-term statistically expected number of fatalities per year*

The risk value of 0,0654 f/year is a low value for an urban motorway tunnel. According to the classification scheme of the Austrian guideline RVS 09.02.31, Tunnel Šentvid can be allocated to danger class II.

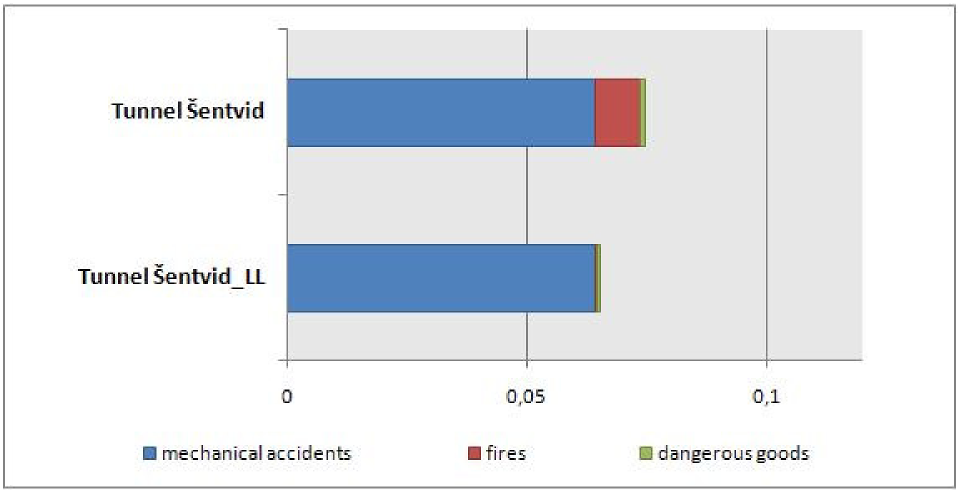
The risk of tunnel Šentvid is dominated by car accidents with mechanical effects. Fire risk is very low, because the tunnel is equipped with a modern longitudinal ventilation system combined with a proper fire detection. However, this is only true, if the emergency mode of the ventilation operates according to newest knowledge about operational strategies for emergency ventilation (PIARC report 2008 "Operational Strategies for Emergency Ventilation" – draft).

- ► the fire is detected without delay
- ► the ventilation starts immediately after detection of the fire and blows the smoke with appropriate air velocity in the direction of traffic
- ► hence, given that there is no tailback in front of the fire, the people in their cars stopping behind the fire scene are protected from smoke and can evacuate towards the next emergency exit.

However, in the course of the study it was detected that the emergency mode of the tunnel ventilation in tunnel Šentvid follows a different philosophy: the ventilation is switched on only approximately 10 minutes after the detection of a fire. During the first phase in a tunnel fire the ventilation is not switched on respectively blows with a very low velocity so that smoke may spread to both directions in the tunnel (back layering – caused by thermic buoyancy). In such situations people may by affected by the toxic gases and their movements toward the emergency exits are handicapped by the smoke (visibility). In severe fires this may cause a considerable risk.

Hence the consequences on risk of these effects were investigated in the risk analysis: it turned out that it could result in a considerable increase of fire risk (results see picture 9).

The study comes to the conclusion that these negative effects can easily be avoided by changing the strategy of emergency ventilation.



Picture 9: Tunnel Šentvid: Effects of alternative emergency ventilation strategy on risk