Mannvit / Spölur

Hvalfjörður Road Tunnel

Contribution to Risk Analysis

April 2013

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List of Contents

1 Introduction

Client	Mannvit / Spölur
Tunnels	Hvalfjörður Tunnel
Status	In operation
Length	5760 m
Speed limit	70 km/h
Road Traffic volume	8230 veh / day in 2033

Table 1.1 Key figures concerning the tunnel

This risk analysis is part of the evaluation of the safety in the Hvalfjörður tunnel. It is the intension that the results of the risk analysis shall support the decision making process concerning the operation and possibly improvement of the tunnel.

The risk analyses are carried out in accordance with the EU Directive for road tunnel safety [13] and the Icelandic regulation 992. The risk analyses are carried out by application of a methodology, which is described in [39] and in chapter 12 of the present document.

The risk analysis takes into account all relevant design factors and traffic conditions known presently that affect safety, notably traffic characteristics, tunnel length, type of traffic and tunnel geometry, as well as the forecast number of heavy goods vehicles per day. The risk analysis is based on available statistical information about traffic accident etc. in Iceland and internationally.

1.1 The object of the analysis

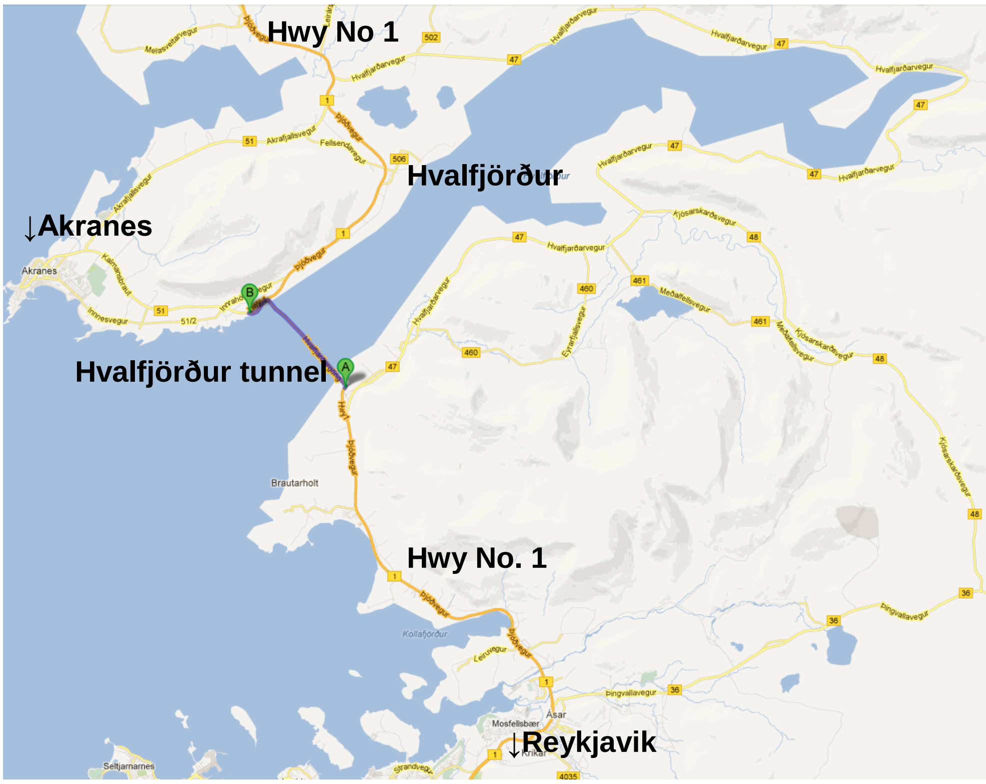


Figure 1.1Location of the tunnel in North of Reykjavik across the Hvalfjörður

The tunnel is located North of Reykjavik as part of the main road 1. The tunnel crosses the Hvalfjörður and with the opening of the tunnel a 42 - 60 km long detour around the fjord was saved.

The tunnel is a toll paid section and a toll booth is located outside the northern portal. The toll booth collect payment both from the northbound and the southbound traffic. In the toll booth also the tunnel control centre is located. The distance from the portal to the toll booth is approximately 350 m. About 100 m further to the North a large roundabout is located. The roundabout connects road number 51 (going to Akranes) to Highway No 1.

1.2 Key facts about the tunnel

- Tunnel length is 5.77 km with portals (5.5 km in rock), of which 3.7 km are below sea
- Deepest point 165 m below sea level.
- The rock cover is minimum 40 m.
- Tunnel width is 8.5 m on south side (2 lanes) and 11 m on the north side (3 lanes).
- The gradient is 4.4% to 7% on south side and 8.1 % on the north side
- Designed in accordance with Norwegian standards for road tunnels.
- Tunnel excavation started in May 1996, and opened for traffic in July 1998.
- Rock support is mainly rock bolts and sprayed concrete.
- Water leakage was treated with grouting and total leakage is < 5 l/s.
- Pumping gallery with 3 high thrust pumps and storage chamber for 7500 m^3
- Water shielding to ensure no dripping on road.
- Four transformer stations in tunnel, all concrete buildings

1.3 The objectives of the risk analysis.

The risk analysis covers Hvalfjörður tunnel as shown in chapter 1. In chapter 4 the tunnel is described in more detail. The risk analysis covers only the tunnel part including the road section just outside the portal..

The analysis focuses on the risk to the users of the tunnel.

The objectives of the risk analysis are:

- To document the risk level of the tunnel and evaluate the risk by comparison with risk evaluation criteria as well as evaluate if further risk reducing measures should be introduced.
- The risk analyses form a part of the operational decision and it supports planning and design of risk reducing measures (comprising structural, mechanical, electrical as well as operational and organisational measures).

The general aims for which the decisions are assumed to follow the policy statement are given below:

Safety
The tunnel shall have a safety level, which does not expose the users to a higher risk than for a comparable open section of road. The additional risk for the population near the tunnel shall be negligible. Possible events with large consequences shall be given special attention.

2 Risk related basis

2.1 General information

Geometry	
Length of tunnel	5.770 km
Max slope	8.1%
Tunnel cross section	T8.5 for 2 lanes section and T11 for 3 lanes section
Walkways	Yes, smooth surface is being installed
Minimum horizontal radius	R = 350 m
Traffic	
Traffic AADT 2013 (2012)	5160 veh/day (5041 veh/day)
Traffic AADT 2033 minimum	7332 veh/day
Traffic AADT 2033 midi	8230 veh/day
Traffic AADT 2033 maximum	11960 veh/day
HGV %	6.5%
Transport of dangerous goods	Partly restricted
Speed limit	70 km/h
Traffic jams	No
Bidirectional traffic	yes
Safety and management systems	
Ventilation	Longitudinal
Natural ventilation	Natural ventilation is 1.5 to 2 m/s towards south without ventilators running, due to geothermal heat source in the south section.
Design fire	35 MW
Minimum air speed provided inside tunnel	Speed varies from 0.1 m/s to 2.5 m/s if all fans are blowing at max. power
Number of fans	32 in 4 groups
CO_2 measurements	If CO_2 > 1000 ppm, all fans automatically turn on
CO measurements	If CO > 1000 ppm for over 15 minutes, the tunnel shuts automatically
Smoke detection	In technical rooms
Safety and management systems	
Rumble strips and LED	Rumble strips on centreline only; no LED on sidewalks
Drainage system	Yes
Luminance	2 cd/m^2
Emergency exits:	No exits, other than portal
Emergency phones	Every 125 m, connects directly to 112
Fire extinguisher	Every 125 m, pairs of 6 kg dry powder ABC rated
Emergency lay bays	Every 500 m, 3 are especially for large vehicles
Automatic speed control	Yes
Turning bays	Every 1500 m. Additional red lights at turning bays
Blinking light and sign to indicate turning bay	Yes, will be installed soon
Markings showing distance to portals	Every km
Markings showing speed limit	yes
Traffic surveillance	CCTV coverage of the whole tunnel. Toll booth operator serves as control centre / tunnel operator
Speed Camera for ticketing	Several speed cameras in the tunnel, operated by the police department in Reykjavik
Variable signs to inform drivers of their speed	No
Red lights to indicate tunnels are closed	At both portals
Physical barrier to stop traffic.	At both portals
Automatic incident detection	Yes (but slow?)
Communications	Tetra and GSM
Radio interruption	Yes radio can be interrupted manually from the toll booth

Table 2.1 Key information about the design and equipment in Hvalfjörður Tunnel.

2.2 Traffic

The following information about the traffic is used as basis for the risk analysis:

- Traffic volume per tube (including its time distribution),
- Presence and percentage of heavy goods vehicles,
- Risk of congestion (daily or seasonal),
- Speed limits for the traffic and its enforcement

2.2.1 Traffic prognosis

The traffic prognosis is discussed in appendix chapter 10: For the year 2013 and 2033 the traffic is expected as shown in Table 2.2. The traffic is close to be the same in both directions.

Hvalfjordur Tunnel		[veh/d]			
	Pct.	2013	2033 low	2033 med	2033 high
AADT (PV + other) tunnel	93.5%	4825	6855	7695	11183
AADT (HGV) tunnel	6.5%	335	477	535	777
AADT (total) tunnel	100%	5160	7332	8230	11960

Table 2.2 Traffic prognosis for Hvalfjörður Tunnel

The distribution of traffic is described in detail in the document Hvalfjarðar-göng, Umferðarúttekt – Umferðarspá [4]. In Figure 2.1, Figure 2.3, **Error! Reference source not found.** below illustrate the distribution over the day, week and year for the year 2004 (where AADT was 4103 veh/day). The traffic has a peak in the afternoon and is higher on Friday and Sunday

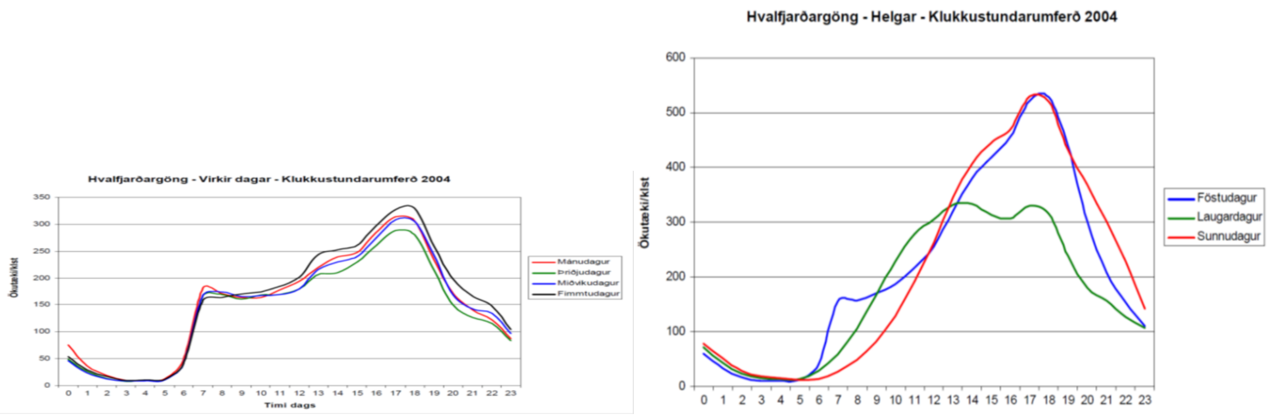


Figure 2.1 Traffic distribution over day. Left: Monday-Thursday, right Friday – Sunday.

Based on the above mentioned traffic prognosis, the hourly traffic is forecasted the daily distribution of the traffic in 2013 and 2033 will be as illustrated in **Error! Reference source not found.**. Peak traffic occurs at weekends and in the summertime.

<u>Hourly traffic 2033 (using middle traffic forecast)</u>

- afternoon peak: approximately 700 veh/h (average day)
- The peak hour traffic in weekends in the summer time (Fri/Sun; July) will presumably be approximately 1400 veh/h in 2033.

<u>Hourly traffic 2033 (using low - high traffic forecast)</u>

- afternoon peak: approximately 600 – 1000 veh/h (average day)

- The peak hour traffic in weekends in the summer time (Fri/Sun; July) will presumably be approximately 1200 - 2000 veh/h in 2033.

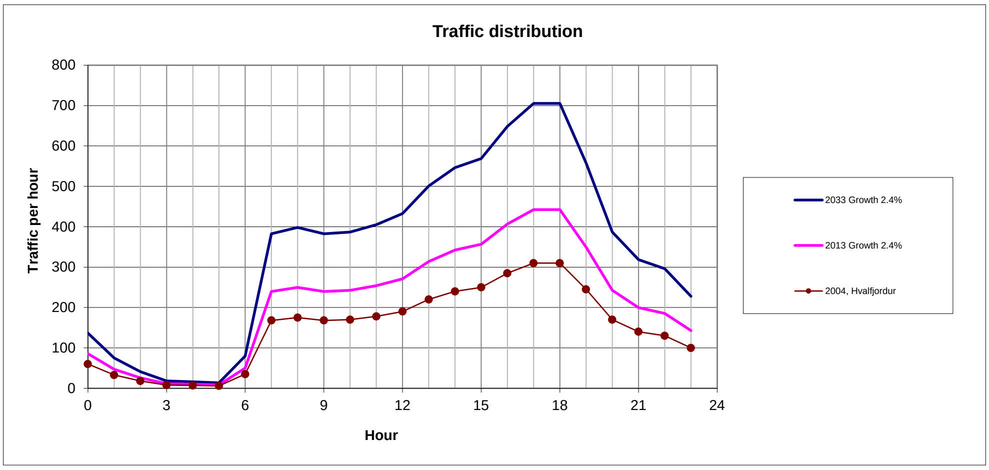


Figure 2.2 Assumed daily distribution of the traffic forecasted for 2013 and 2033 based on the registration of 2004 and using the middle traffic forecast.

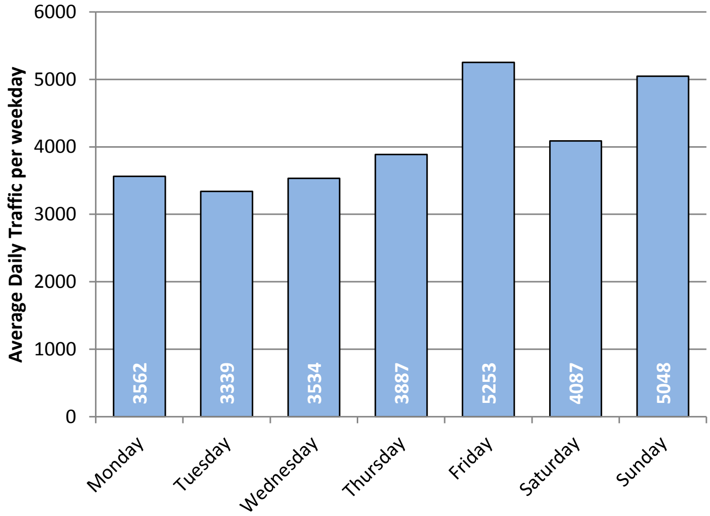


Figure 2.3 Traffic distribution over the week (2004 figures)

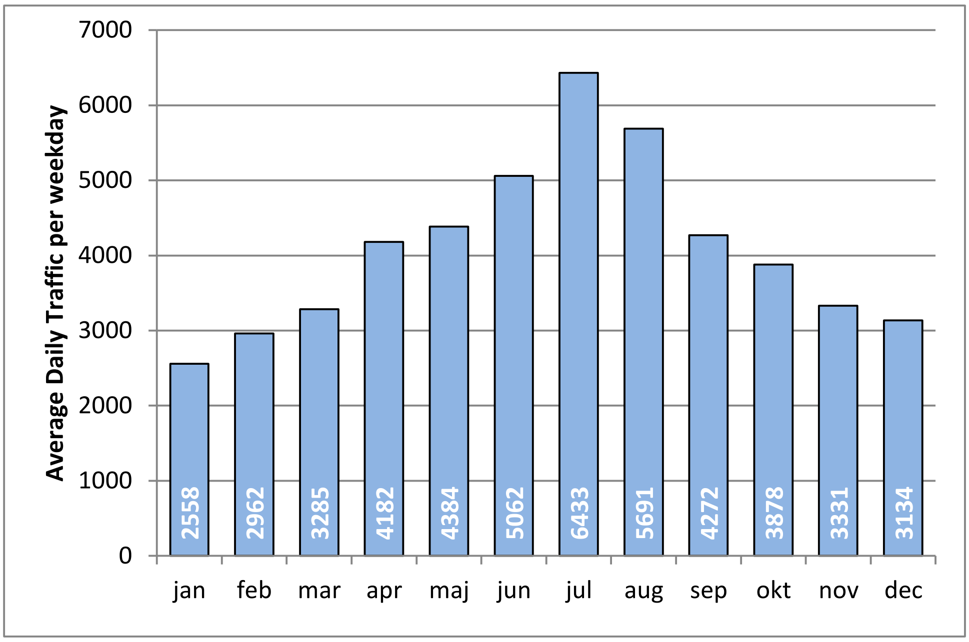


Figure 2.4 Traffic distribution over the year (2004 figures)

<u>Portion of traffic with buses</u>
It is assumed that the traffic with buses is 2% of the AADT, which is a relative high share of the traffic.

<u>Portion of heavy traffic</u>
Based on the registration in 2004 the percentage of heavy goods vehicles (HGVs) was 6.5%. This figure is used in the present risk analysis.

Dangerous goods

Traffic with dangerous goods is restricted in peak hours, as defined below:

	Peak hours
Monday	15:00 – 20:00
Tuesday	15:00 – 20:00
Wednesday	15:00 – 20:00
Thursday	15:00 – 20:00
Friday	10:00 – 01:00
Saturday	07:00 – 01:00
Sunday	07:00 – 01:00

Table 2.3 Peak hours where dangerous goods is restricted

It is estimated that the transport of dangerous goods transports is 0.11% of the AADT, which corresponds to 1.7% of the HGV traffic. In absolute numbers this is in average 6 vehicles per day in 2013 and 9 vehicles per day in 2033 based on the middle traffic forecast.

Year 2033	Total Mill veh-km	nHGV traffic Mill veh-km	DGHGV traffic Mill veh-km	Buses Mill veh-km	PV traffic Mill veh-km
Low	15.4	1.0	0.017	0.31	14.1
Middle	17.3	1.1	0.019	0.35	15.8
High	25.2	1.6	0.028	0.50	23.0

Table 2.4 Summary of traffic in 2033. nHGV denotes heavy goods vehicles without dangerous goods. PV denotes personal cars

2.2.2 Capacity / Traffic congestion

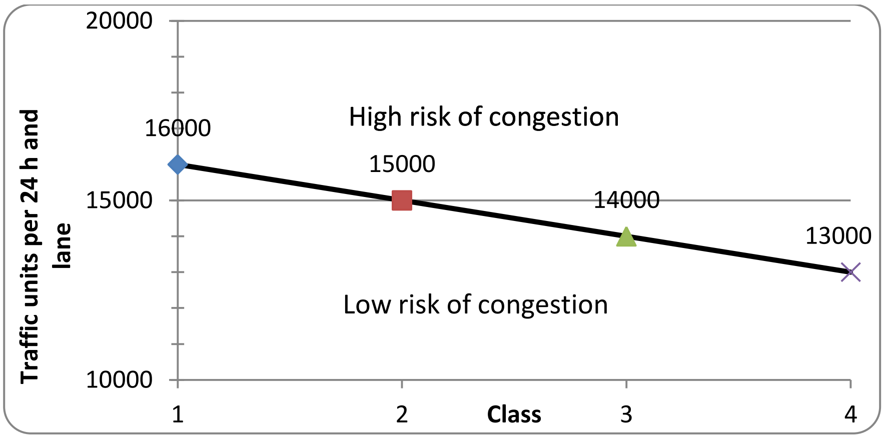
At present there is no problems of congestion in the Hvalfjörður tunnel. With increasing traffic it might occur that the traffic will line up at the toll booth. In order to evaluate the risk of congestion the capacity of the road through the tunnel has been estimated. The capacity is described as follows [4]:

Practical capacity of the upgrade in the south end of the tunnel is calculated with a methodology developed by PIARC (World Road Association). Practical capacity varies, among other variables, with grade and proportion of heavy vehicles in the traffic flow. Calculated practical capacity during a Friday peak hour is 1,170 vphpl (vehicles per hour per lane). During peak hours on Sundays practical capacity is 1,370 vphpl. Assuming that proportion of heavy vehicles is 10% practical capacity is 980 vphpl.

As it appears the traffic will approach the capacity in the end of the time interval regarded.

The risk of congestion can also be evaluated based on the guidelines. The AADT of 8230 veh/day is assumed distributed approximately 50%/50% in the two directions, and the HGV share is 6.5% and the share of buses is 2%. On this basis the vehicle units per 24 hours and lane (according to ASTRA 13 001, see Figure 2.5) can be determined to 4000 – 6500 PWE (middle approximately 4500 PWE) per direction under normal conditions in 2033.. At peak hours during weekend and at the summer time the hourly traffic may reach 8000 – 13000 PWE (middle 9000) around the end of the considered time period.

Figure 2.5 illustrates that (in case of Class 1: combined long distance- commuter and local traffic) a high risk of congestion occurs if the traffic units per 24 h and lane are more than 16000 PWE. For tunnels with holiday traffic and traffic from tourist centres the limit of the high risk of congestion is met at 13000 PWE.



Class 1: Long distance, combined long distance- and commuter traffic, commuter traffic and local traffic.
Class 2: Regional traffic.
Class 3: Holiday traffic.
Class 4: Tourist traffic to and from tourist centres.
PWE (traffic units) is based on AADT and average share of heavy vehicles (1 HGV = 2 PWE).
Classes are related to the prevailing purpose of the traffic. At merging lanes in or near the tunnel limits are reduced 20%. If this is the case the limit for class 1 is 12800.

Figure 2.5 Frequency of congestion (corresponding to Figure II.2 in ASTRA 13 001) in tunnels with unidirectional traffic characterised as high or low frequency of congestion.

It appears that there is not a high risk of congestion in the tunnel at normal operation. At 2033 congestion might be expected at weekends and during summer.

2.2.3 Speed limits

The speed limit in the tunnel is 70 km/t, and the speed limit is enforced by automatic traffic cameras..

2.3 General accident frequencies for Iceland

2.3.1 IRTAD

From IRTAD (OECD - International Road Traffic and Accident Database) the following information about accidents in Iceland has been taken. The figures for Iceland shown in Table 2.5 are in accordance with the low end of the West-European frequencies given in the IRTAD statistics,[17].

Fatal Accidents 2010	IRTAD	
All roads	$2.5\ 10^{-9}$	fatalities per veh-km
Accidents 2006		
All roads	--	accidents per veh-km

Table 2.5 Frequencies of accidents and fatalities in Iceland for 2008 [17].

Frequency of fatalities on all roads is 2.5 fatalities per billion veh-km (2010 – statistics), which is a very low figure compared with other Nordic countries and compared with European countries. However, the Icelandic statistics appears to be more volatile than other statistics (presumably because of the relatively few number of accidents) – and the accident rate was in 2009 with 8.0 fatalities significantly higher (and higher than other Nordic and European countries). If the development is drawn up for the years 1980 – 2010 the tendency in the fatality rate can be observed. Even though the Icelandic fatality rates have significantly higher scatter (and the development seems to have a minimum in the mid-1990'ies and a high point in the early 00'ies), the trend lines might describe the development well. The trend lines shown Figure 2.6 are established from Norwegian data, where the curve with the sharpest reduction is established as a best fit of an exponential curve and the other two curves show a possible relationship with less reduction in the fatality rate.

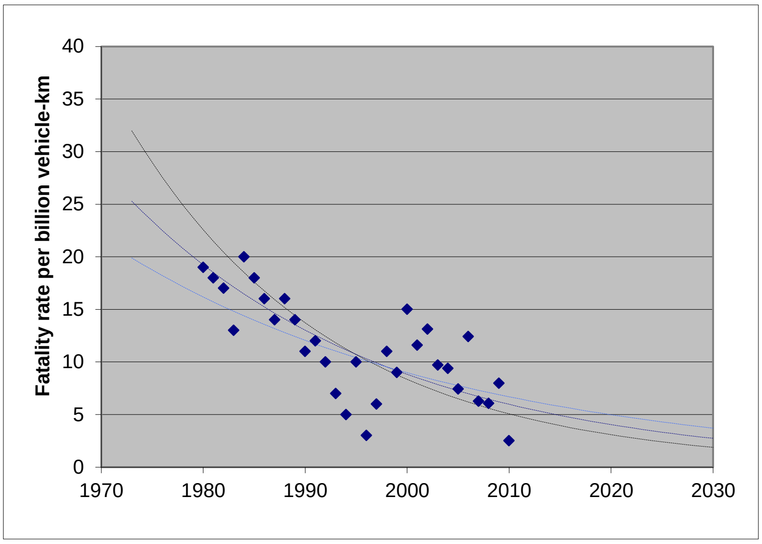


Figure 2.6 Fatality rates in Iceland 1980 to 2010 and trend lines established based on Norwegian data.

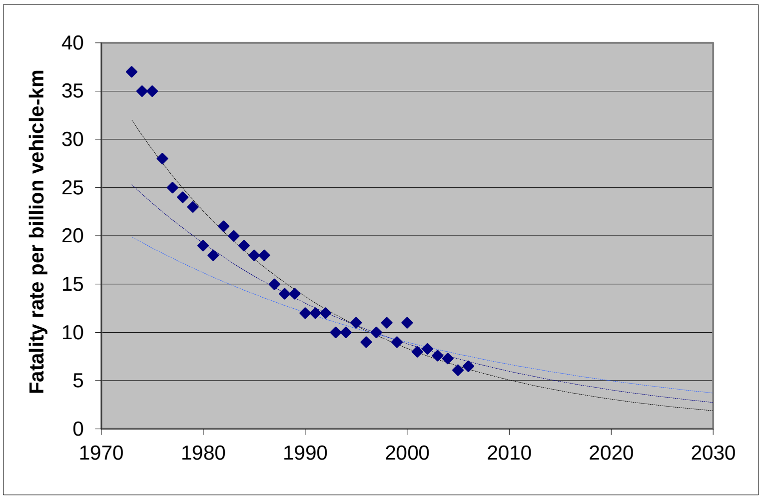


Figure 2.7 Fatality rates in Norway 1970 to 2010 and trend lines.

It may be concluded that the approximation of using Norwegian basic data is appropriate.

The accident rates, both with respect to the number of accidents per year accidents per vehicle km and fatalities and injuries per year and per vehicle km, are far from constant with time. The accident frequencies since the late 1970'ies have followed closely a decreasing exponential trend line. (Actually also in the period before 1970). The continuation of this trend line would mean a reduction of the frequency of injury accident per vehicle km in the year 2033 to between ¼ and ½ of the frequencies of 2008. Using the frequencies of today as basis for the risk analysis will obviously derive an upper value of the future risk.

Whereas the development in occurrence of accidents is clearly decreasing, the consequences in terms of fatalities per incident and injuries per incident are nearly constant: 1.13 fatalities per fatal accident, 0.091 fatalities per injury+fatal accident and 1.37 injuries per injury+fatal accident.

3 Risk policy and risk acceptance

The purpose of the risk analysis is discussed in section 1.3. The general policy given in section 1.3 will have to be formulated in terms of risk acceptance criteria in order to be part of the risk evaluation. The policy concerned with safety was formulated as: *"The tunnel shall have a safety level, which does not expose the users to a higher risk than for a comparable open section of road. The additional risk for the population near the tunnel shall be negligible".*

3.1 Risk acceptance criteria

ALARP

It is suggested to formulate the risk acceptance criteria as an ALARP criterion (As Low As Reasonably Practicable). The definitions, which include an upper limit and a region in which cost-benefit type of evaluations are made, are shown in Figure 3.1.

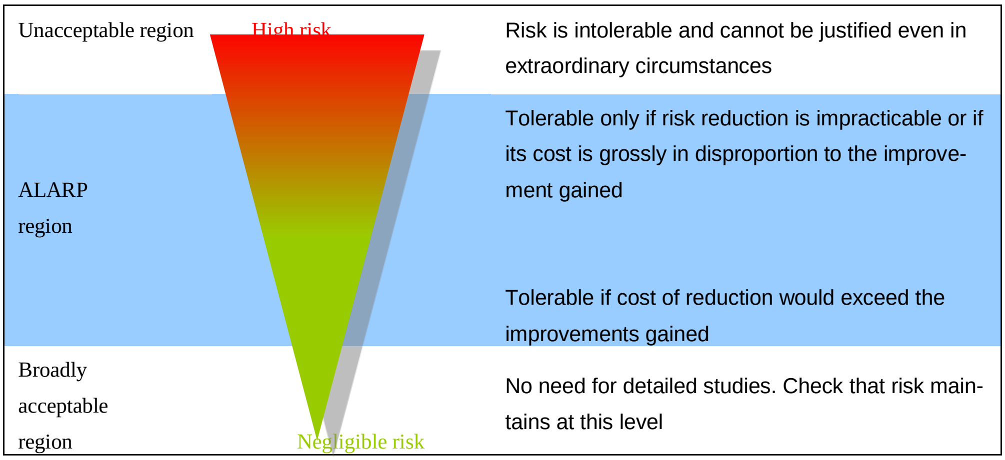


Figure 3.1 ALARP region and acceptance limits.

The upper limit, which under no circumstances may be exceeded, is specified here to 1.5 times the general risk of fatalities on roads in Iceland. When the IRTAD [17] data for Iceland is used, this gives the absolute upper limit of 1.5 x 6 fatalities per billion vehicle km = 9 fatalities per billion vehicle km. In the ALARP zone below this limit risk reducing measures must be introduced unless their cost is (grossly) in disproportion to the improvements gained.

It must be stressed that the upper limits represent a risk which may not be exceeded at any circumstances. Below this limit the risk may still have to be reduced depending on the cost benefit relation of the possible risk reducing measures.

Average in Iceland 2010	6	fatalities per billion veh km
Absolute upper limit	9	fatalities per billion veh km
Hvalfjörður tunnel		
Traffic volume 2033	16.2	million veh km/yr
Upper limit	0.15	fatalities/yr

Table 3.1 Absolute upper limit for the Hvalfjörður Tunnel for the traffic in 2033.

In addition to the upper limit, the risk can be compared to the risk of a "reference tunnel" which is designed according to the guidelines without any special characteristics or deviations.

Weight factors
In connection with the ALARP principle it is necessary to associate the various types of consequences / risk with weight factors, which can facilitate comparison. For the present study the weight factors have been based on a rough estimate using the values which are common practice in other Nordic countries such as Norway and Finland.

	2033 EUR
Fatalities	3000000
Very severe injuries	1500000
Severe injuries	400000
Light injuries	75000

Table 3.2 Weight factors for personal damages

Large accidents and risk aversion
Large accidents with many fatalities are often regarded as worse than several smaller accidents with the same total number of fatalities. That means one accident with 10 fatalities is regarded worse than 10 separate accidents with each one fatality.

Even though this is disputable, this option is often taken into account in risk analyses for tunnels. There are several ways to give priority to large accidents.

In the present risk analysis, the risk aversion is not treated specifically. Risk aversion might be quantified in the next phases of the risk analyses. In the mitigation measures, however, care should be taken to prevent accidents with a large number of fatalities or injuries.

Disruption of traffic / Traffic disturbance
Disruption of traffic and traffic disturbance can be a major consequence of events in the tunnel. Particularly for a tunnel located in an urban area the traffic can be significantly influenced and disturbed if the traffic is redirected. In the present preliminary study the traffic disturbance is not included specifically as part of the consequences of events. It is assumed, however, that the roads on the surface can be used in case of temporary closure of the tunnel in one or both directions.

4 Definition of the tunnel system

4.1 Geometry

The tunnel is located North of Reykjavik as part of the main road 1. The tunnel crosses the Hvalfjörður and with the opening of the tunnel an approximately 42 to 60 km long detour around the fjord was saved.

The tunnel is a toll paid section and a toll booth is located outside the northern portal. The toll booth collect payment both from the northbound and the southbound traffic. In the toll booth also the tunnel control centre is located. The distance from the portal to the toll booth is approximately 350 m. About 100 m further to the North a large roundabout is located. The roundabout connects road number 51 (going to Akranes) to Highway No 1.

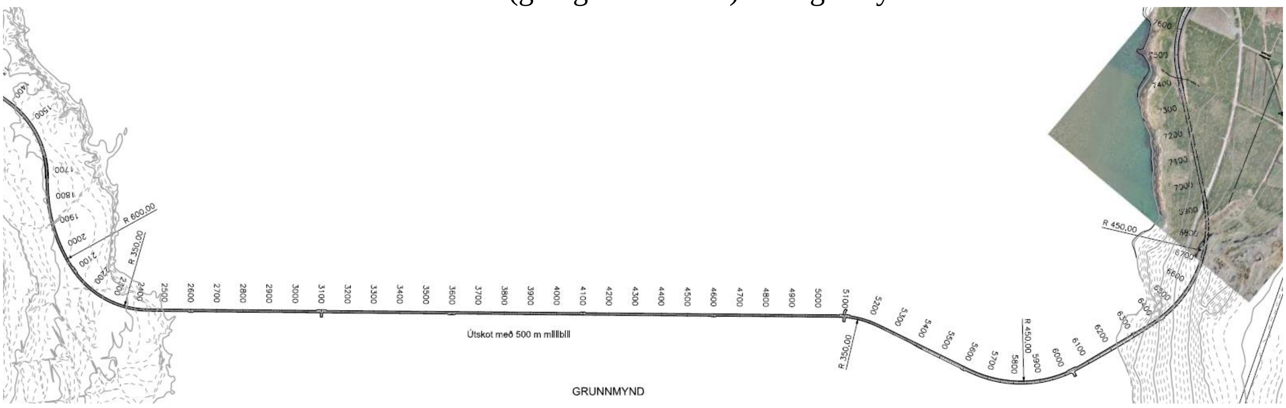


Figure 4.1 Alignment of the tunnel (North to the right)

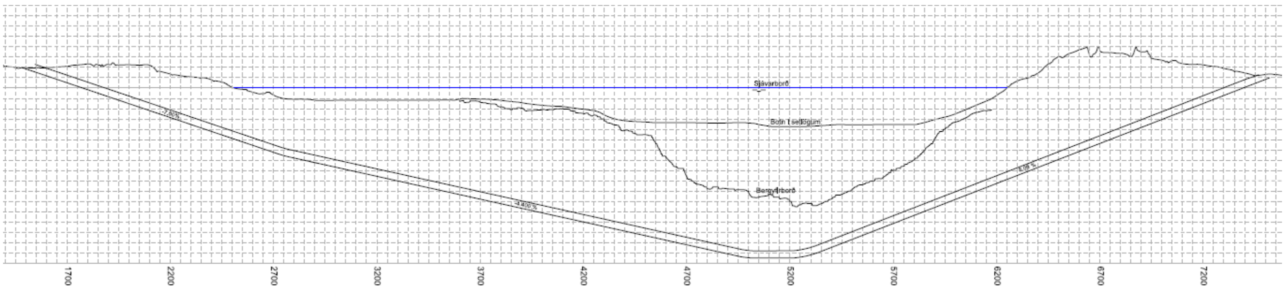


Figure 4.2 Longitudinal profile for Hvalfjörður Tunnel (North to the right)

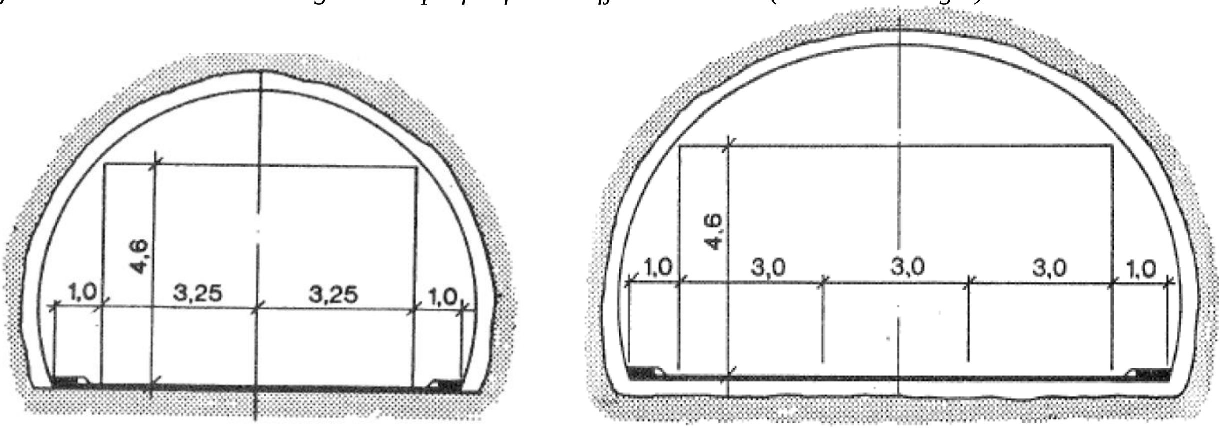


Figure 4.3 Principal lay-out of cross section of tunnel (unit: m).

4.1.1 Alignment, Tunnel sections

The horizontal alignment of the tunnel is shown in *Figure 4.1*. For the description of the alignment the tunnels have been divided into 18 sections.

North bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
	S Portal							
H1n		1590	50	350	-7	1	3.25	4115
H2n		1640	50	350	-7	1	3.25	4115
H3n		1690	100	600	-7	1	3.25	4115
H4n		1790	360	600	-7	1	3.25	4115
H5n		2150	320	350	-7	1	3.25	4115
H6n		2470	240		-7	1	3.25	4115
H7n		2710	2290		-4.4	1	3.25	4115
H8n		5000	110		0	1	3.25	4115
H9n		5110	90	350	0	1	3.25	4115
H10n		5200	200		8.09	1	3.25	4115
H11n		5400	250		8.09	2	3.00	4115
H12n		5650	400	450	8.09	2	3.00	4115
H13n		6050	360		8.09	2	3.00	4115
H14n		6410	490	450	8.09	2	3.00	4115
H15n		6900	350		8.09	2	3.00	4115
H16n		7250	100		8.09	2	3.00	4115
H17n		7350	50		8.09	2	3.00	4115
H18n	N Portal	7400	50		8.09	2	3.00	4115

South bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
	S Portal							
H1s		1590	50	350	7	1	3.25	4115
H2s		1640	50	350	7	1	3.25	4115
H3s		1690	100	600	7	1	3.25	4115
H4s		1790	360	600	7	1	3.25	4115
H5s		2150	320	350	7	1	3.25	4115
H6s		2470	240		7	1	3.25	4115
H7s		2710	2290		4.4	1	3.25	4115
H8s		5000	110		0	1	3.25	4115
H9s		5110	90	350	0	1	3.25	4115
H10s		5200	200		-8.09	1	3.25	4115
H11s		5400	250		-8.09	1	3.00	4115
H12s		5650	400	450	-8.09	1	3.00	4115
H13s		6050	360		-8.09	1	3.00	4115
H14s		6410	490	450	-8.09	1	3.00	4115
H15s		6900	350		-8.09	1	3.00	4115
H16s		7250	100		-8.09	1	3.00	4115
H17s		7350	50		-8.09	1	3.00	4115
H18s	N Portal	7400	50		-8.09	1	3.00	4115

Table 4.1 The tunnel geometry and traffic. The tunnel is for the description divided into 18 sections in each direction. Traffic AADT is given for the year 2033 and covers each direction.

4.1.2 Cross sections

With the width of 3.00 and 3.25 m respectively the lanes are relatively narrow. A walkways with 1.00 m width is located on both sides of the road, the walkway did not at the opening of the tunnel have an even and fixed surface. However, this is being upgraded and autumn 2012 the Northern half of the tunnel had walkways with fixed even surface.

The tunnel walls are uneven and rough in surface, resulting from the construction / blasting process.

The road marking on a 2,5 km straight part of the road in southern part of tunnel is according to 23. Paragraph in the Icelandic Road Authority regulation nr. 289/1995 on marking the surface of road where is written: „a line (three times as long as the gap) means that caution should be used crossing it and is not allowed unless with utmost precaution“ see picture This solution has given a good result and no accidents has been experienced.

Figure 4.4 Road markings according to Icelandic Road Authority regulation nr. 289/1995

4.1.3 Lay bys

The lay-bys are located at the following locations:

				Distances: Lay-bys (m)		
	point	Type	Side	L	R	Turning bay
1	2100	SP	L		510	1510
2	2600	N	R	1000		
3	3100	SN	L		1000	
4	3600	SP	R	1000		
5	4100	N	L		1000	
6	4600	N	R	1000		2930
7	5100	SN*	L		1000	
8	5600	N	R	930		
9	6030	SN	L		830	
10	6430	N	R	890		
11	6920	SP	L		480	1800

Table 4.2 Location and distance between lay-bys and turning point.
Legend: L: left; R: right, Type SP, SN and N, see figure below.SN: Two-lane turning bay.*

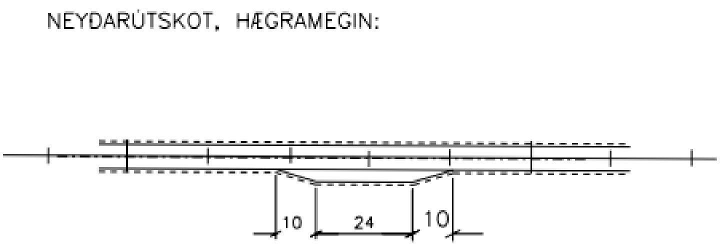


Figure 4.5 Lay-by type N (R: right) (unit: m).

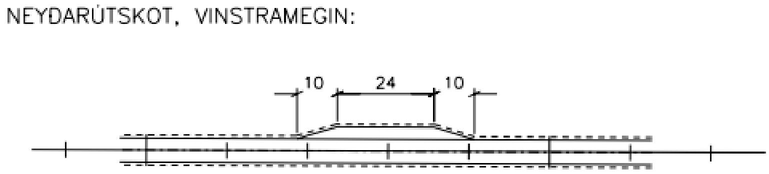


Figure 4.6 Lay-by type N (L: left) (unit: m).

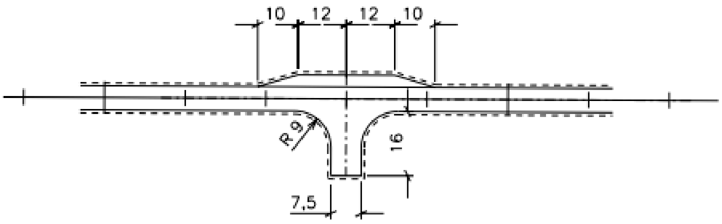


Figure 4.7 Lay-by type SN, turning bay (unit: m).

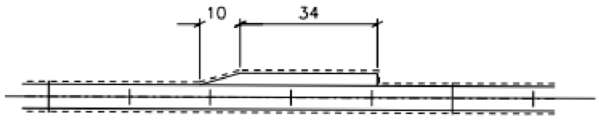


Figure 4.8 Lay-by type SP (unit: m).

4.2 Ventilation

The tunnel has longitudinal ventilation, which is a common system for tunnels with low traffic in Nordic countries. The design fire is 35 MW, which is less than the requirements for a tunnel of class C.

As a special feature the natural ventilation gives an air movement of 2 m/s in the Southern direction. The underground thermal heat is driving the air flow.

4.3 Tunnel lighting

The light in the tunnel has been improved and the luminance of the tunnel light has been measured in order to control the compliance with the regulation (i.e the Norwegian HB021). The measurements [9] documented that the luminance is 2 cd/m^2 in the interior of the tunnel and higher in the entrance and exit zones. This is sufficient when the traffic is less than AADT 8000 veh/d. With AADT over 8000 veh/d the luminance shall be minimum 4 cd/m^2.

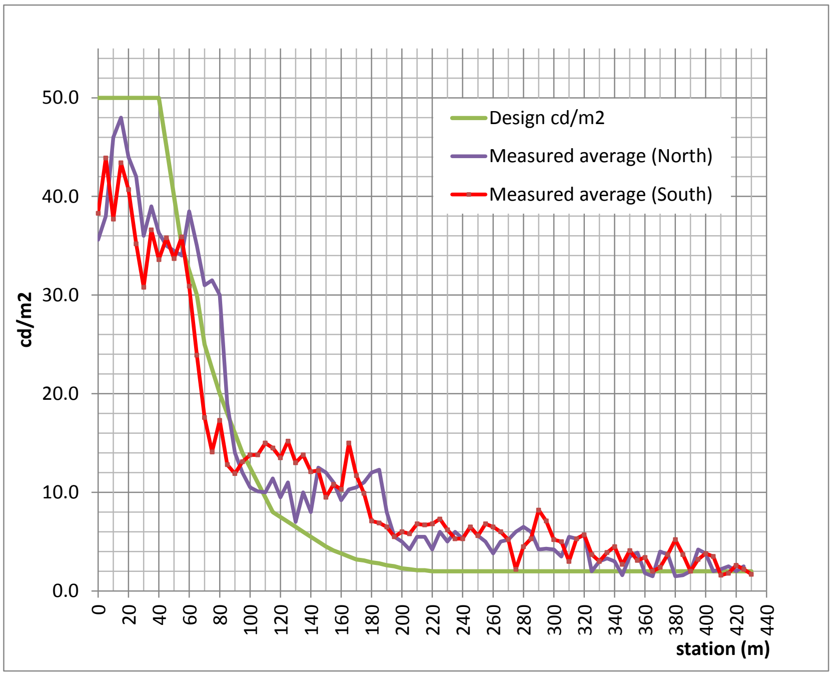


Figure 4.9 Lighting in Hvalfjörður Tunnel at North and South portal. Comparison of measurements with requirements (ref. HB021 [14])

The measurements of the luminance are illustrated in Figure 4.9. The measurements show that the requirements are fulfilled well. In the first 50 m the luminance is slightly below the requirements, whereas the luminance appears to be over the requirements for the remaining part of the measured section.

4.4 Other safety equipment

The available safety equipment is listed in chapter 2, as tunnel characteristic it can be highlighted that the following will be available during 2013:

- The tunnel is supplied with "rumble stripes" between the directions This will to some extent reduce the risk of collision between vehicles in two directions. It was deemed not possible to have rumble stripes along the walkway, because the HGVs on the narrow road would constantly be travelling on the stripes and causing noise in the vehicles.
- The walkways will be given a fixed surface.
- Fire extinguishers (two at each location) will be installed at intervals of 125 m.
- All traffic signals will be installed with internal lighting
- Messages can be broadcasted to tunnel users over the FM radio frequencies.
- Red stop lights will be installed at all turning points, which makes it possible to stop the traffic at these locations, where the vehicles can turn.
- CCTV is installed in the entire tunnel
- AID (automatic incident detection) is installed
- The tunnel is operated from the toll booth, which also includes the monitors for the cameras/AID and the radio-rebroadcasting system.
- All cables are class II or class III
- Smoke detectors are installed in all technical rooms
- The water isolation is provided by a fire proof (poly ethylene) fabric.

5 Identification of tunnel characteristics

Critical or unusual parts of the tunnel system will be identified. The identification can among others be supported by the reference of tunnel guidelines and the herein specified minimum safety requirements.

Critical items typically include among others: slopes, horizontal curves, vertical curvature, ventilation principle, risk of congestion, speed, traffic composition, dangerous goods, portals, junctions, etc.

In the EU directive for minimum safety requirements [13], it is specified that safety measures to be implemented in a tunnel shall be based on a systematic consideration of all aspects of the system composed of the infrastructure, operation, users and vehicles. The parameters to take into account are specified.

The Hvalfjörður Tunnel has special characteristic as regards some of the aforementioned parameters. Consequently the risk analysis shall establish whether additional safety measures and/or supplementary equipment are necessary to ensure a high level of tunnel safety. The special characteristics for the Hvalfjörður Tunnel comprise:

- <u>Tunnel cross section</u>
  The tunnel has a single tube cross section with one – two driving lanes per direction (in total two – three lanes). The lanes are relatively narrow: 3x 3.00 m for the three lane section and 2x 3.25 m for the two lane section. The two lanes uphill has generally a risk reducing effect, (compensating partly the risk increasing effect of the steep gradient), on the other hand the quite narrow lanes tend to increase the risk of accidents and consequence of accidents.
- <u>Tunnel structure</u>
  The rough surface of the walls in the tunnel can contribute to more severe consequences of accidents involving collision with the walls. The walkways with smooth surface may tend to reduce the risk of collision with the walls. The shoulders without surface (which were in the tunnel from the opening until 2012 – 2013) do not correspond to normal practice in other countries and would imply a higher risk.
- <u>Traffic level</u>
  With the level of traffic expected in the tunnel (in 2033) it is not expected that congestion will occur as a result of traffic overload on normal days. However in the summer period and in weekends it is not unlikely that congestion will occur.

  According to for example the Norwegian tunnel guideline, two tubes with each two lanes shall be constructed, when the AADT is over 12000 vehicles per day at a time 20 years after opening. The Norwegian tunnel guideline calls for emergency exits every 500 m (and thereby a parallel tunnel tube) when AADT is over 8000 veh/d. The traffic will reach this level before 2033 only if the increase in traffic will be as high as the medium traffic forecast or more.

- HGV percentage
  Generally heavy vehicles contribute more to the risk than smaller and lighter vehicles.

  The share of 6.5% HGVs of the total traffic in Hvalfjörður Tunnel is relatively low compared to the average of 12%- 15%. This contributes to a slightly lower occurrence of accidents and fires and to less consequences of fires.

- Gradients
  For the accidents statistics large gradients are regarded as adverse and are discouraged in the tunnel safety guidelines and EU directive.

  The gradients on the slopes in the Hvalfjörður tunnel is with 7%-8% in most of the tunnel length very high. The EU directive (2004/54/EC) does make an exemption for the maximum slope of 5% where no other solution is geographically possible. The Norwegian guideline has included this as exemptions for sub-sea tunnels: For AADT > 1500 veh/d, the maximum gradient is specified to 7%. It is also stated that sub-sea tunnel of local character with low traffic can have gradients up to 10% (but this will have to be approved on an individual basis).

  Hvalfjörður tunnel complies with the condition of being a sub-sea tunnel, but is not a tunnel of local character with low traffic. The limit based on the Norwegian guideline would be 7%.

  In any case the high gradients will contribute to a higher risk. Gradients higher than 3% shall according to the EU directive be included in the risk analysis. In the present risk analysis the influence of the slope has been included in the estimation of occurrence of stopped vehicles, accidents and fires.

- Horizontal curves
  The minimum radius is minimum of 350 m. Small radiuses tend to increase the risk, but in the actual case where the speed limit is 70 km/h the increase is relatively small.

- Speed
  The speed limit is relatively low compared to the general statistics for tunnel which is based on an average speed limit of 80 km/t. The risk reduction for a considered speed of 70 km/h compared to a reference speed of 80 km/h is taken into account and will counteract the above mentioned risk increasing design features. In addition to the speed limit, an enforcement with automatic traffic cameras is introduced. The enforcement contributes to a lower average speed and a narrower distribution of speeds compared to other road sections with a speed limit of 70 km/t.

- Light
  Bright lighting in tunnels reduce the risk of accidents. The Hvalfjörður tunnel has lighting conditions corresponding to the Norwegian guidelines. On the other hand the tunnel has often dust problems which tend to reduce the visibility.

- Ventilation
  The tunnel has longitudinal ventilation. The design fire is 35 MW, which is less than the requirements for a tunnel of class C. The ventilation may for this reason be unable to control the fires. If back-flow results of smoke exposure of an area where intervention or evacuation is taking place, then this may cause injuries or even fatalities. On tunnel with steep gradients it is particularly difficult to control severe fires and prevent back-flow.

  The ventilation is taken into account in the quantitative risk analyses.

- Monitoring and alarm
  Surveillance, monitoring and alarm are available and are controlled from the toll booth. The working conditions in the toll booth is, however, not optimal, because the staff responsible for the tunnel operation is also responsible for the collection of toll. Better working conditions and staffing of the operation could contribute to more reliability of the response in case of incidents and accidents.

- Dangerous Goods
  Dangerous goods has been banned from the tunnel in peak hours. This is obviously a risk reducing measure for the tunnel. It shall be noted that transports banned from the tunnel might take other routes where incidents also may have serious consequences.

- Natural risks
  The tunnel may be exposed to natural risks such as flooding, earthquakes and other natural events which may occur at this location. These risk are not included in the present risk analysis. In case these risk factors should be included a separate analysis would have to be carried out. It is assumed, however, that the contribution from natural risks to the total risk for tunnel user is moderate.

6 Quantitative risk analysis

The risk analysis is carried out with the use of the quantitative risk analysis tool "TRANSIT", which has been applied in conjunction with a Swiss – Norwegian research project [39]. The use of the program has been adapted to Icelandic conditions.

In the present report the calculations have been carried out for the selected situations of 2013 and 2033. The results shall form the contribution to a risk analysis of the Hvalfjörður tunnel. Additional calculations and evaluations may be included in the process of finalisation of the risk analysis.

6.1 Stopped vehicles

The general frequencies for breakdowns are between 5 and 12 per million vehicle km (ref. [16]) and there is a tendency to an increased number of breakdowns in tunnels with uphill slopes. These figures have not been adapted to Icelandic conditions.

With the medium traffic estimate for 2033 and the above assumptions it is expected that the number of breakdowns is 160 per year as a low estimate and 400 per year as a high estimate (Low traffic estimate: 150 – 350 breakdowns; high traffic estimate 240 – 580 breakdowns). The gradients result in an increase of the rates of 100% (doubling the number of motor stops). There might be stopped vehicles on the ramps, which are not included in the above figures.

In general the most common cause of break downs is motor stop (50% of the cases) followed by lack of fuel (25% of the cases).

6.2 Accidents, Fires and Dangerous Goods Events

6.2.1 Hvalfjörður 2013

In addition to the tunnel characteristics directly included in the models of the analysis tool, the following has been taken into account:

Characteristic	Modification
Rough walls	Modification by increase factor of 1.15 on frequency of injury accidents
Monitoring and alarm	Modification by increase factor of 1.4 on frequency of fires and 1.15 on injury accidents
Ventilation system (35 MW).	Insufficient ventilation modelled as natural ventilation
Banning of DG from rush hours.	Risk is reduced to 20% of the value calculated for a tunnel without restrictions

The summary of the results is shown in Table 6.1 and in Figure 6.1 - Figure 6.5, which are illustrating the profile of accidents and fatalities along the tunnel alignment.

Hvalfjörður Tunnel			
	Number killed / year	Number injured /year	Number events /year
Accidents	0.0923	2.344	1.636
Fires	0.0126	0.187	0.840
Dangerous goods	0.0000	0.000	0.000
Total	0.1049	2.531	2.475
Traffic	11.04		Mill. veh-km/yr
Accident rate	0.148		Per Mill. veh-km
Fire rate	0.076		Per Mill. veh-km
Fatality rate	9.51		Per Bill. veh-km

Table 6.1 Summary of estimated risk for 2013 with speed limit 70 km/t.

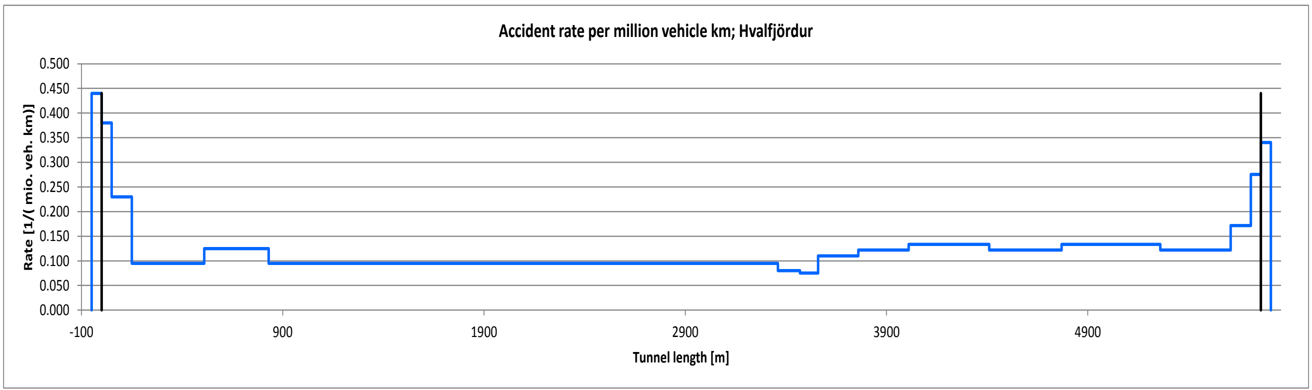


Figure 6.1 Accident rate per segment and million vehicle km in Hvalfjörður Tunnel 2013 Northbound direction. North is to the right at the first axis.

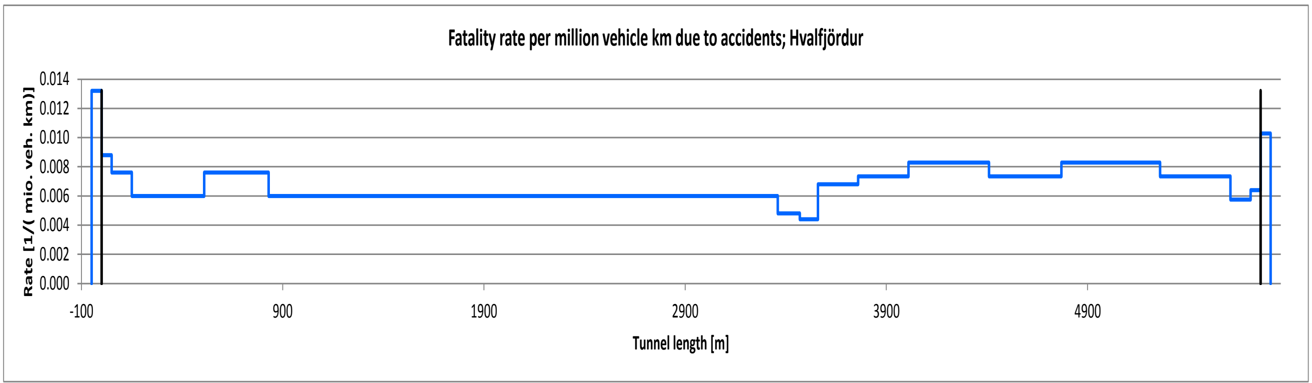


Figure 6.2 Fatality rate per segment and million vehicle km in Hvalfjörður Tunnel 2013 Northbound direction. North is to the right at the first axis.

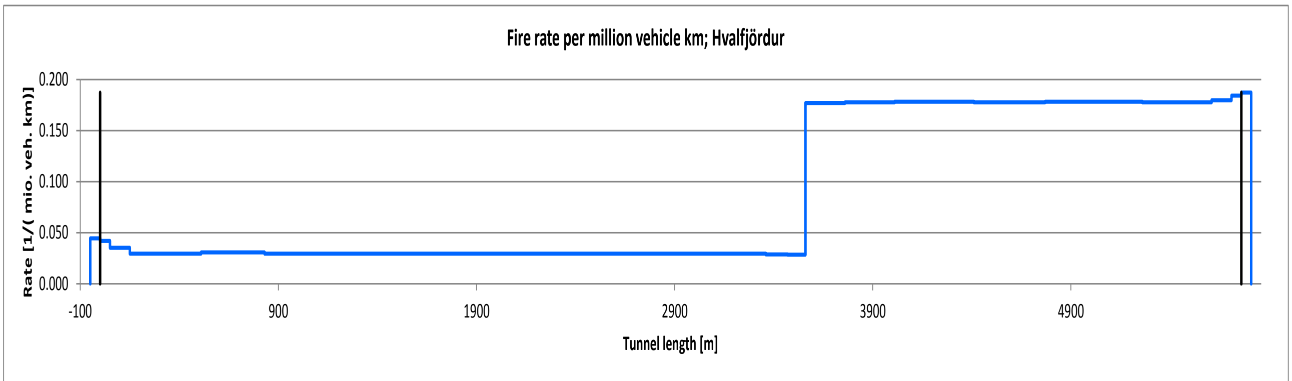


Figure 6.3 Fire rate per segment and million vehicle km in Hvalfjörður Tunnel 2013 Northbound direction. North is to the right at the first axis.

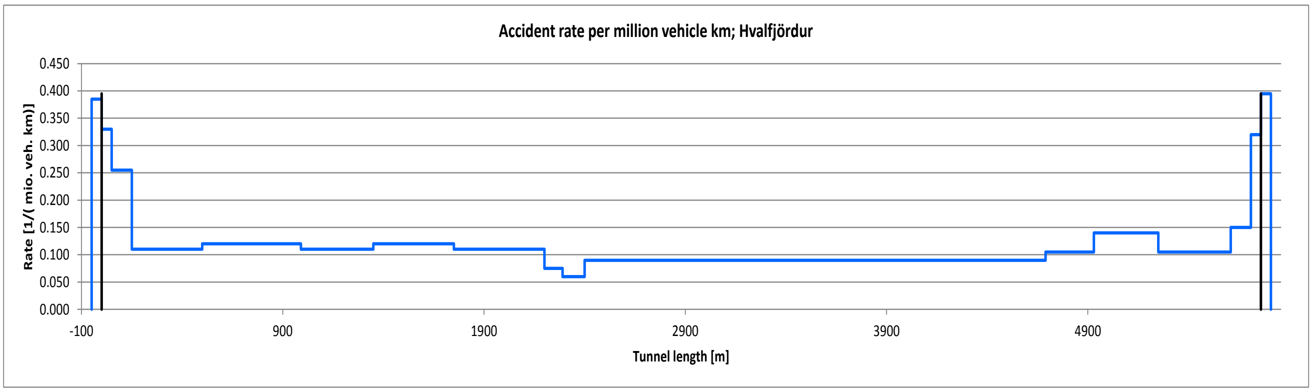


Figure 6.4 *Accident rate per segment and million vehicle km in Hvalfjörður Tunnel 2013 Southbound direction. South is to the right at the first axis.*

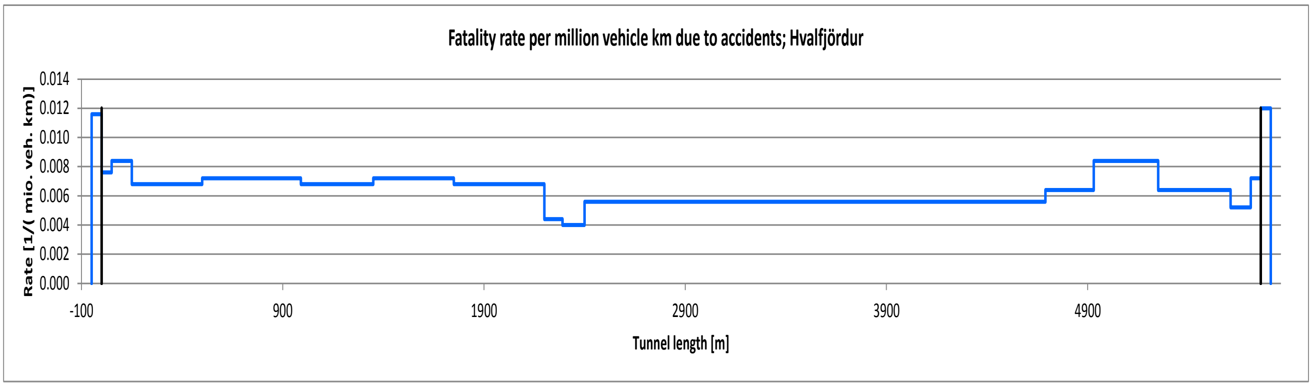


Figure 6.5 *Fatality rate per segment and million vehicle km in Hvalfjörður Tunnel 2013 Southbound direction. South is to the right at the first axis.*

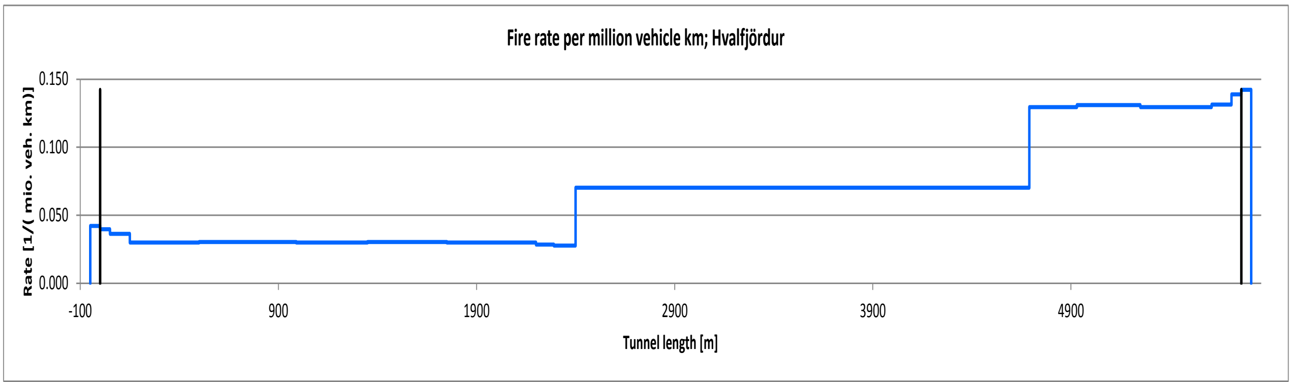


Figure 6.6 *Fire rate per segment and million vehicle km Hvalfjörður Tunnel 2013 Southbound direction. South is to the right at the first axis.*

The graphical illustration illustrates the influence of the tunnel characteristics. The influence of the portals, the gradients and the curvature is clearly illustrated.

The summary reveals that the fatality rate is higher than the upper limit and also higher than the reference tunnel. The speed limit of 70 km/h (and the automatic traffic camera) contributes to a lower fatality risk and also the two lanes on the 8.1% uphill part, and the relative low percentage of HGVs contribute to a lower risk. However, these measures do not fully compensate for the increase in risk from e.g. steep gradients, narrow road lanes, rough tunnel walls, and insufficient ventilation system.

The dominating cause of injuries and fatalities are traffic accidents, severe fires occur significantly less frequently (even with the assumption of the insufficient ventilation system).

The risk contribution from dangerous goods events is extremely low. With the restrictions of transports in rush hours the contribution from dangerous goods transports is negligible compared to other serious events. Even without restrictions the contribution from dangerous goods transports to the total risk would be low.

In Figure 6.7 the so-called FN-curve for fatalities resulting from dangerous goods transported is presented for a 100 m section of the tunnel, under the assumption of no restrictions to dangerous goods transports. The illustration and the limits is shown similar to the practice in Switzerland, and it appears that the risk is far below the lower limit of concern.

The value of the intersection of the FN-curve with the second axis is the number of dangerous goods accidents with 1 fatality or more on a 100 m average section of the tunnel.

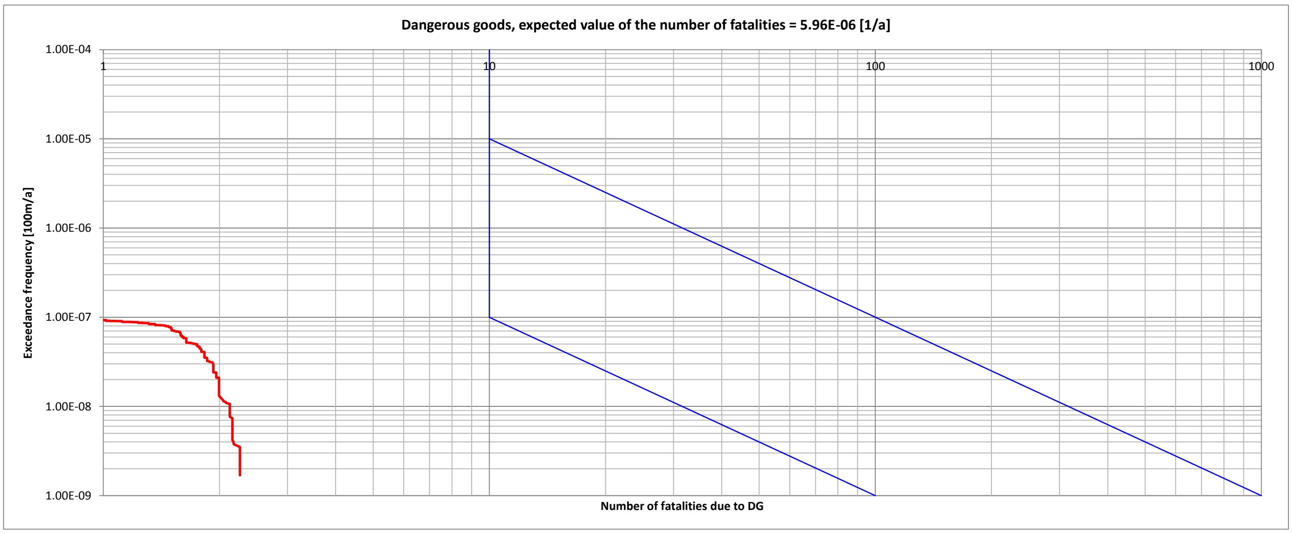


Figure 6.7 FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, northbound, 2013.

6.2.2 Hvalfjörður 2033

With increasing traffic the risk may increase not only in terms of events per year but also in terms of accident and fatality rates. For the year 2033 (20 years from now) the following risk estimates have been calculated.

The traffic for 2033 has been estimated in chapter 2.2.1. In the following the risk is presented for the middle traffic estimate. In addition to the traffic estimate it is assumed that congestion will occur 200 hours per year (peak hours in summer and weekends). All other assumptions are the same as for the calculations for 2013.

The summary of the results is shown in Table 6.1 and in Figure 6.1 - Figure 6.5, which illustrate the profile of accidents and fatalities along the tunnel alignment.

Hvalfjörður Tunnel				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.1521	3.916	2.709	
Fires	0.0308	0.298	1.338	
Dangerous goods	0.0001	0.000	0.000	
Total	0.1830	4.215	4.047	
Traffic	17.60		Mill. veh-km/yr	
Accident rate	0.154		Per Mill. veh-km	
Fire rate	0.076		Per Mill. veh-km	
Fatality rate	10.40		Per Bill. veh-km	

Table 6.2 Summary of estimated risk for 2033 with speed limit 70 km/t.

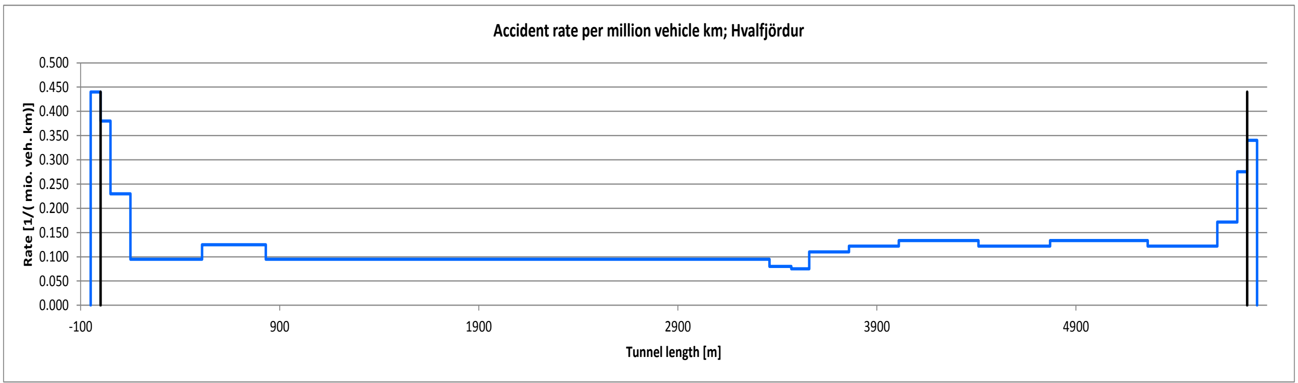


Figure 6.8 Accident rate per segment and million vehicle km in Hvalfjörður Tunnel 2033 Northbound direction. North is to the right at the first axis.

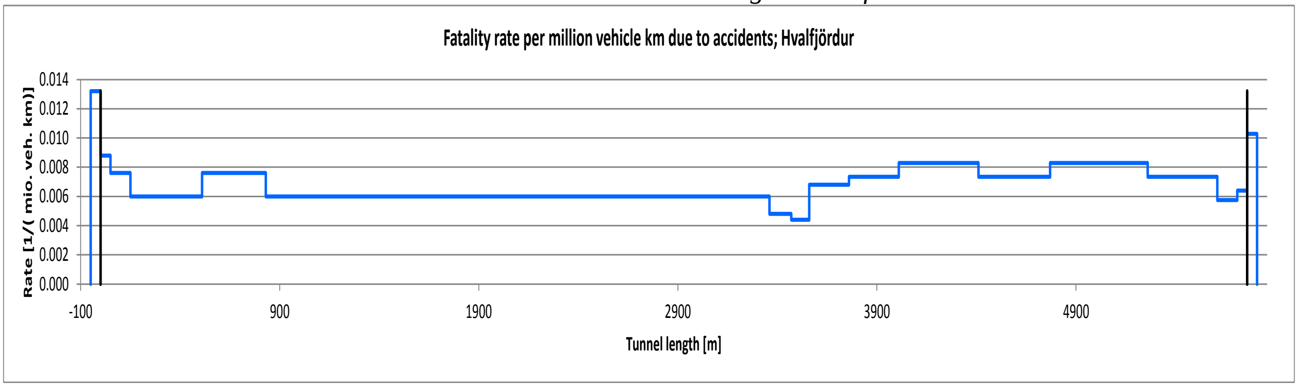


Figure 6.9 Fatality rate per segment and million vehicle km in Hvalfjörður Tunnel 2033 Northbound direction. North is to the right at the first axis.

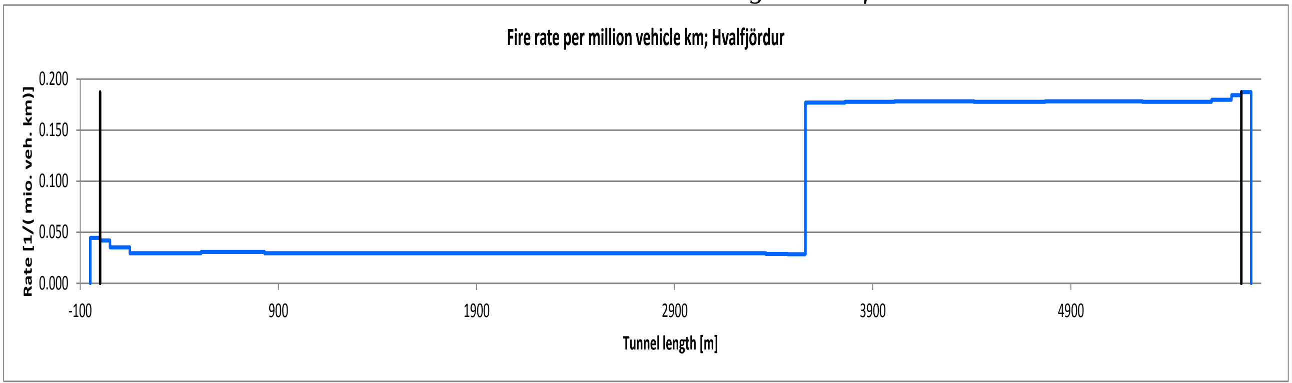


Figure 6.10 Fire rate per segment and million vehicle km in Hvalfjörður Tunnel 2033 Northbound direction. North is to the right at the first axis.

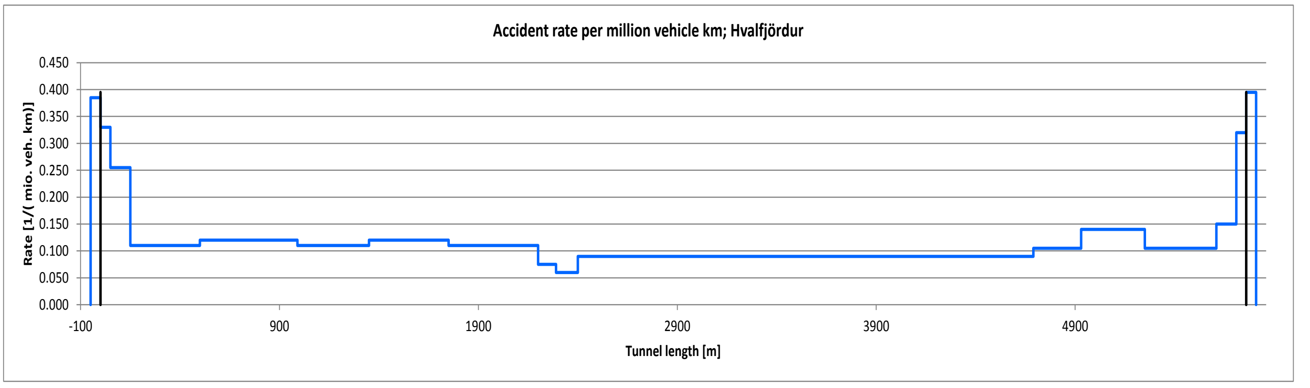


Figure 6.11 *Accident rate per segment and million vehicle km in Hvalfjörður Tunnel 2033 Southbound direction. South is to the right at the first axis.*

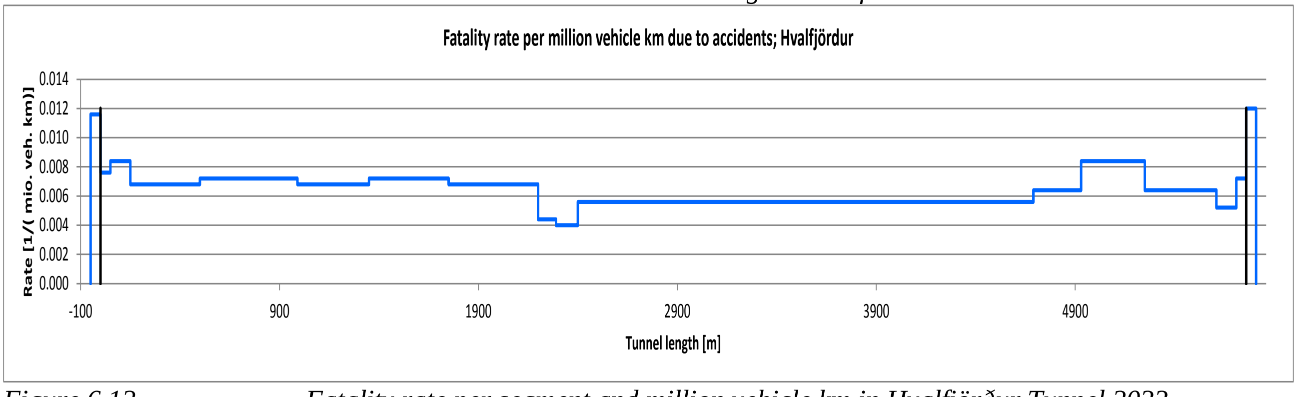


Figure 6.12 *Fatality rate per segment and million vehicle km in Hvalfjörður Tunnel 2033 Southbound direction. South is to the right at the first axis.*

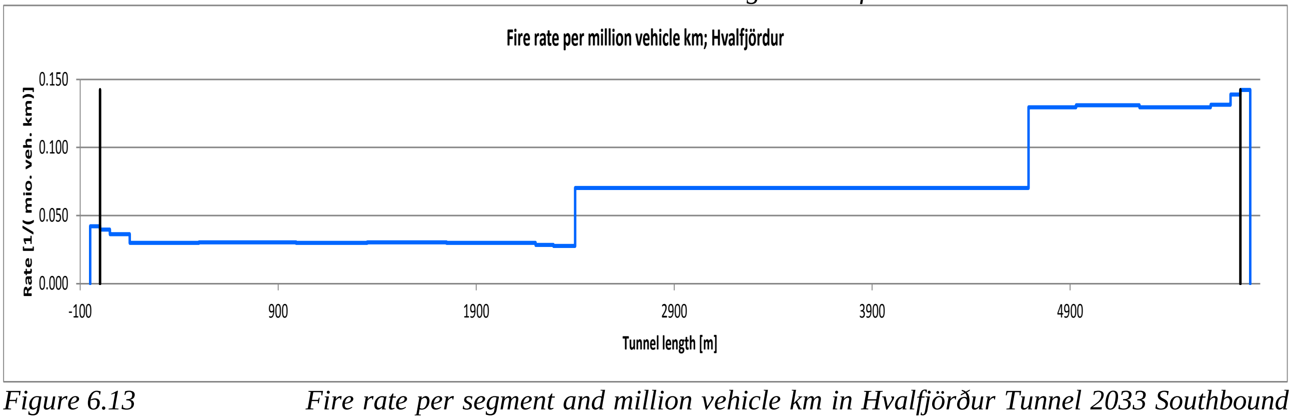


Figure 6.13 *Fire rate per segment and million vehicle km in Hvalfjörður Tunnel 2033 Southbound direction. South is to the right at the first axis.*

With an increased traffic density the rate of accidents increase and the possible consequences of fires increase. The increase also affect the dangerous goods accidents, and the F-N curve for the unrestricted transport of dangerous goods is in 2033 over the lower limit but still below the upper limit. This means that risk reducing measures will have to be introduced based on the ALARP principle.

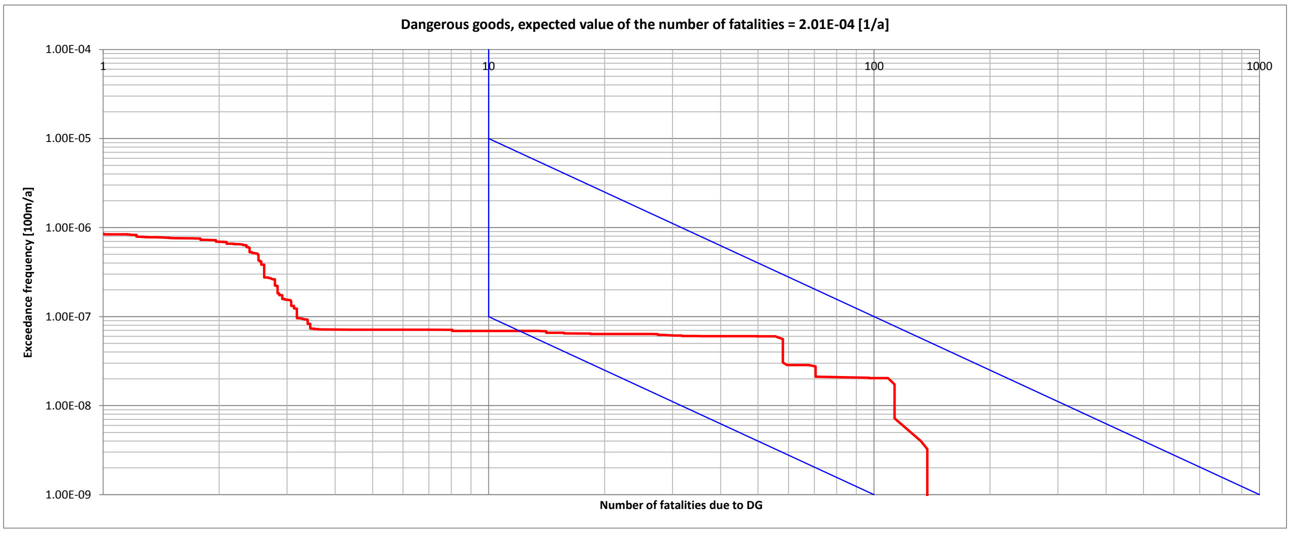


Figure 6.14 FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, northbound, 2033.

Figure 6.15 FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, northbound, 2033.

Low and high traffic forecast

Similar to the above figures for 2033 based on the middle traffic forecast, the risk can be determined for the low and the high traffic estimate.

Hvalfjörður Tunnel 2033 Low			
	Number killed / year	Number injured /year	Number events /year
Accidents	0.1290	3.323	2.298
Fires	0.0254	0.266	1.192
Dangerous goods	0.0000	0.000	0.000
Total	0.1545	3.589	3.490
Traffic	15.68	Mill. veh-km/yr	
Accident rate	0.147	Per Mill. veh-km	
Fire rate	0.076	Per Mill. veh-km	
Fatality rate	9.85	Per Bill. veh-km	

Table 6.3 Summary of estimated risk for 2033 with the low traffic estimate with speed limit 70 km/t.

Hvalfjörður Tunnel 2033 High				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.2710	6.947	4.825	
Fires	0.0468	0.446	1.982	
Dangerous goods	0.0001	0.000	0.000	
Total	0.3179	7.394	6.807	
Traffic	25.58		Mill. veh-km/yr	
Accident rate	0.189		Per Mill. veh-km	
Fire rate	0.077		Per Mill. veh-km	
Fatality rate	12.43		Per Bill. veh-km	

Table 6.4 Summary of estimated risk for 2033 with the high traffic estimate with speed limit 70 km/t.

With 65% more traffic the number of accidents and fatalities is nearly doubled. It can be seen that the fatality rate is 25% higher for the high estimate than for the low estimate. In both cases the fatality rate is quite high and over the established limits.

6.2.3 Risk reducing measures

The results show that the risk (measured as fatality rate) is slightly over the upper limit (approximately 10%- 30% over the limit in 2033 and 5%- 10% in 2013). This means that it is mandatory to introduce risk reducing measures in order to bring the risk under the upper limit. Measures which are planned and which also for reasons of compliance with the guidelines are necessary will most likely result in reduction of the risk of minimum 10%. In addition to this, risk reducing measures shall be introduced in accordance with the ALARP principle.

In the longer term more significant improvements will have to be implemented in order to keep the risk below the upper limit.

For this reason the risk reducing measures are divided into the measures which can be carried out within the next 1-2 years, and other measures, which may be implemented within approximately 10 years.

Short term

In the short term the following measures are evaluated and proposed:

- Monitoring: Monitoring with CCTV and AID and a control centre manned 24/7 with staff dedicated to the monitoring and control tasks
- Ventilation: Specific studies of the ventilation and possibly improvement to fulfil the requirements of controlling a 50 MW fire under all weather conditions and with the redundancy of jet fans falling out near to the fire. In addition a study of the improvements possible by an actively controlled ventilation.
- Rumble strips at the central divide and at the walkways in order to reduce the risk of frontal collisions and collisions with the wall.
- LED lights along the curb of the walkways in order to clearly indicate the limitation of the road lane. These may function as emergency lights, or separate emergency lights may be installed.
- Possibly "guides" (or/ crash barriers) along the walls in order to reduce the consequences of a collision.

- Light: The risk calculations indicate that it will be a possibility to reduce the risk by improved lighting. It is recommended to carry out detailed investigations of improved light with a luminance of 4 cd/m^2 in the interior of the tunnel and corresponding improvement of the light in the adaptation zones.

With these improvements, the risk is calculated as follows:

Hvalfjörður Tunnel				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.0586	1.518	1.057	
Fires	0.0035	0.052	0.887	
Dangerous goods	0.0000	0.000	0.000	
Total	0.0621	1.570	1.944	
Traffic	11.61		Mill. veh-km/yr	
Accident rate	0.091		Per Mill. veh-km	
Fire rate	0.076		Per Mill. veh-km	
Fatality rate	5.35		Per Bill. veh-km	

Table 6.5 Summary of estimated risk for 2013 with speed limit 70 km/t, with the upgrade-programme mentioned above.

By the means of these upgrading measures, the risk is reduced to a level corresponding to similar roads in the open. It may even be considered whether the improvement of the light and the guides is cost efficient. On the other hand, in the longer term these measures shall be introduced anyway in order to fulfil the requirements.

The distribution of the risk along the alignment is similar to the figures above.

With increasing traffic volume the risk will increase slightly and with the above-mentioned upgrade package and the middle traffic estimate, the risk in 2033 will be as shown in Table 6.6. As it can be seen the fatality rate will only increase marginally..

Hvalfjörður Tunnel				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.0887	2.297	1.598	
Fires	0.0080	0.077	1.319	
Dangerous goods	0.0000	0.000	0.000	
Total	0.0967	2.374	2.917	
Traffic	17.60		Mill. veh-km/yr	
Accident rate	0.091		Per Mill. veh-km	
Fire rate	0.075		Per Mill. veh-km	
Fatality rate	5.49		Per Bill. veh-km	

Table 6.6 Summary of estimated risk for 2033 (middle traffic estimate) with speed limit 70 km/t, with the upgrade-programme mentioned above.

Longer term

An efficient (albeit also relatively expensive) risk reduction can be achieved by constructing a parallel tunnel tube. It is here assumed that the tube is constructed with the same longitudinal profile (which give the possibility of constructing cross passages, but on the other hand implies an increased risk due to the high gradients).

The improvements introduced in the upgrade mentioned above will of course be kept and will be introduced in the second tube as well. The second tube is assumed to have 2 lanes both 3.5 m wide all through the tunnel.

The corresponding risk is calculated for the middle traffic estimate for 2033, where the traffic is estimated to 8230 veh/day. For the low traffic estimate the same traffic will be expected in 2040 and for the high traffic estimate it will be reached in 2024. Consequently the risk result below can also indicate the risk after update in 2024 in case of the high traffic estimate and after update in 2040 for the low traffic estimate.

Hvalfjörður Tunnel				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.0590	1.513	1.047	
Fires	0.0042	0.044	1.295	
Dangerous goods	0.0000	0.000	0.000	
Total	0.0632	1.558	2.342	
Traffic	17.60		Mill. veh-km/yr	
Accident rate	0.060		Per Mill. veh-km	
Fire rate	0.074		Per Mill. veh-km	
Fatality rate	3.59		Per Bill. veh-km	

Table 6.7 Summary of estimated risk for 2033 (middle traffic estimate) with speed limit 70 km/t, with the upgrade-programme mentioned above.

By constructing a second tunnel tube the risk can be kept at the same level as for motorways in the open. An increase of the speed limit might even be considered in this tunnel configuration.

7 Summary, conclusion and risk evaluation

The Hvalfjörður tunnel has in the present report been studied. The risk to the users during operation of the tunnel has been estimated. The risk analysis and the study of the tunnel have been carried out in accordance with the EU directive for minimum safety requirements [13] for road tunnels and the best practice for risk analyses [39]. The analysis has been adapted to Icelandic conditions to the extend it is possible.

Hvalfjörður Tunnel has been described and the special characteristics of the tunnel have been discussed and taken into account with both qualitative and quantitative analysis.

The risk has been estimated for the situation as it is today (2013) and in 20 years beyond. The risk has been compared with upper limits of the risk (9.0 fatalities per billion veh-km), the risk in a reference tunnel (in full compliance with the requirements of the standard) and possible risk reducing measures have been considered based on an ALARP approach.

The risk has been estimated by use of a standardised model for quantitative risk analyses. The risk has been estimated for the tunnel and the traffic in 2013 and 2033, if no changes are made. In addition a short-term upgrade has been defined and the risk in the tunnel has been determined with this “upgrade 1”. Finally, an improved tunnel system with two tunnel tubes (“upgrade 2”) has been proposed and the risk has been estimated for 2033. The main results are summarised in the table below:

	Hvalfjörður Tunnel	
	Fatalities /billion veh-km	Fatalities/year
Reference		
2013	6.82	0.0752
2033	5.74	0.1011
Without upgrading		
2013	9.51	0.1049
2033	10.40	0.1830
Upgrading 1		
2013	5.35	0.0621
2033	5.49	0.0967
Upgrading 2		
2033	3.59	0.0632

Table 7.1 Summary of the results of the risk analyses (for the middle traffic forecast).

Monitoring:	Monitoring with CCTV and AID and a control centre manned 24/7 with staff dedicated to the monitoring and control tasks
Ventilation:	Specific studies of the ventilation and possibly improvement to fulfil the requirements of controlling a 50 MW fire under all weather conditions and with the redundancy of jet fans falling out near to the fire. In addition a study of the improvements possible by an actively controlled ventilation..
Rumble strips	Rumble strips at the central divide and at the walkways in order to reduce the risk of frontal collisions and collisions with the wall.
LED lights	LED lights along the curb of the walkways in order to mark the limitation of the road lane. These may function as emergency lights, or separate emergency lights may be installed.
Guides	Possibly “guides” (or crash barriers) along the walls in order to reduce consequences of collisions.
Light	Light: Specific studies of improved light with a luminance of 4 cd/m^2 in the interior of the tunnel and corresponding improvement of the light in the adaptation zones.

Table 7.2 Safety measures in ”upgrading 1”

New tube	An addition parallel road tube with two road lanes which gives the possibility of one-way traffic in each tube.

Table 7.3 Safety measures in "upgrading 2" in addition to "upgrading 1"

Evaluation

The risk estimation shows that the risk in the tunnel as it is today is higher than the upper limit and higher than the risk in the reference tunnel. The risk exceed the upper limit with approximately 10% and it is 25% over the risk in the reference tunnel.

With implementation of the upgrading package 1 the risk can be brought to a level comparable with normal roads in Iceland and below the risk in the reference tunnel. The measures in upgrading package consist of the six improvements mentioned in the table 7.2.

Particular notice should be given to the monitoring. It is suggested to establish a proper control centre for Hvalfjörður Tunnel or for a group of tunnels in Iceland. With a control centre manned 24/7 with dedicated staff, much better working conditions can be provided, and the safety in the tunnel can be improved.

The improvement in the upgrading 1 package may not be sufficient to remain acceptable conditions in longer terms. It is proposed to construct a parallel tunnel tube so that the traffic can be conducted as one-way traffic in each tube. This constellation will provide a significant improvement of the capacity and reduce the frequency and severity of accidents. In addition, the ventilation system will be both more simple (ventilation always in the direction of the traffic) and more safe (no persons in the tunnel part whereto the smoke is blown). It can be considered whether the new tube can be constructed with a less steep gradient. After construction of a second tunnel tube it may be considered to increase the speed limit.

Conclusion

The risk in Hvalfjörður is slightly increased with the design, equipment and traffic it has today. The risk can be reduced with relative modest measures in short term, so that it is at a level corresponding to a new tunnel designed fully in accordance with the tunnel guidelines.

In longer terms (approximately 20 years) a second parallel tube should be planned for. If this second tube is constructed the risk will be significantly reduced and will be at a level corresponding to the similar roads in the open. In addition the capacity will be improved.

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9 Appendix: Results of EuroTap review (2010)

The below results of the EuroTap review is quoted and summarised in order to contribute to the description of the tunnel.

The consultant or the Client do not commend the EuroTap review which is not a risk analysis.It is a check list giving points to the various features of the tunnel and does not take into account a number of relevant parameters for the risk estimation in the tunnel.

9.1 Results at a glance

	Tunnel system	Lighting & power supply	Traffic & traffic surveillance	Communication	Escape & rescue routes	Fire protection	Ventilation	Emergency management	**Overall rating**
Weight [%]	14	8	17	11	13	18	11	8	
Hvalfjörður	Acceptable	Poor	Poor	Acceptable	Very poor	Very poor	Very poor	Very poor	**Very poor**

9.2 Single results (Hvalfjörður tunnel)

Overall rating: **Very poor**
Location: Iceland near Akranes, Hwy No. 1 between Reykjavik and Akranes
Year opened: 1998
Length: 5770m
Portal height level: 10/20 above sea level
Number of tubes: 1/ bi-directional traffic
Speed limit: 70kph
Vehicles per day: 5400
Share of HGVs: 5%
Breakdowns/accidents/ fires in 2006: 26/ 8/ 0
Risk: Medium

Strengths

- Traffic lights and barriers in front of the portals
- Traffic radio throughout the tunnel, the operator can broadcast messages
- Video surveillance with cameras around every 525 m.
- Automatic detection of emergency phone or fire extinguisher use
- Lay-bys provided every 500 metres
- Emergency phones provided every 500 metres
- Fire extinguishers provided every 250 metres
- Tunnel control centre manned around the clock by trained staffl
- Radio communications possible throughout the tunnel for tunnel staff, police and fire brigade
- Emergency response plan is complete

Weaknesses

- Lighting too weak
- No loudspeakers
- Full video surveillance is not possible
- No automatic detection of traffic disruptions, the use of lay-bys, emergency phones or fire extinguishers
- The distances between fire extinguishers of 250 m is too long
- Escape routes are not marked by evacuation lighting and are poorly signposted
- No additional escape or rescue routes
- No automatic fire alarm system
- In the event of fire, ventilation is not automatically activated
- Ventilation control in the event of fire is not sufficiently effective and not sufficiently monitored
- The ventilation section to extract smoke runs the entire length of the tunnel, i.e. 5770 metres, and

is hence too long
- Emergency response plan out of date
- Distance to be covered by fire brigade, i.e. 28 kilometres, is too long
- Only one hydrant in the middle of the tunnel
- The maximum time of use for the fire brigade's respiratory equipment is too short
- The power supply and local power supply are not protected against power failure
- Safety-relevant cables are not sufficiently fire-resistant
- No system in place to quickly drain flammable and toxic liquids
- No regular training or emergency drills

Plans for the future

- 2010: Improved markings for lay-bys; additional fire extinguishers; batteries for the uninterruptible power supply system to be supplemented/replaced
- 2011: Additional video cameras and transmission via optical fibres; additional emergency phones with fire extinguishers and improved markings
- 2012: Escape route signs in the tunnel; new cabling for evacuation lighting
- 2012/ 2014: Installation of an automatic video surveillance system; automatic extinguishing system in the transformer stations; certified cables for power supply and control

Briefly and to the point:

- The medium risk found for driving through the tunnel is primarily due to the tunnel length of 5,770 metres and the steep gradient of more than eight percent. On the other hand, the traffic volume of 5,400 vehicles per day and the number of hazardous goods transports are rather low.
- Preventive measures are acceptable, at least with a view to the structure, and primarily comprise sufficiently wide lanes and lay-bys. However, lighting is too weak. The tunnel is monitored around the clock in a tunnel control centre manned by trained staff, however, video surveillance is incomplete.
- Incidents in the tunnel are not automatically reported to the tunnel control centre. Tunnel staff are forced to rely on reports made by motorists using either the emergency phones or their own mobile phones. If necessary, motorists are guided using traffic lights and variable traffic signs and information is provided on displays and traffic radio. There is no automatic fire alarm system; this means that if a fire breaks out, the tunnel control centre must activate the ventilation system manually, close the tunnel and notify the fire brigade. The long distance to be covered by the fire brigade and the insufficient supply of fire-fighting water with just one hydrant in the middle of the tunnel make fire fighting difficult. At least an emergency response plan co-ordinates co-operation between the tunnel control centre and emergency services. Emergency drills are not held regularly.
- The preconditions for effective self-rescue in a fire need to be improved badly. Due to the long ventilation section along the entire length of the tunnel, i.e. 5,770 metres, smoke located a long distance from the seat of the fire cannot be prevented from sinking down from the tunnel ceiling. Moreover, longitudinal flow in the tunnel is not considered in ventilation control. The steep gradient in the tunnel also encourages smoke to spread. This can lead to smoke spreading throughout the entire tunnel and, considering the lack of additional emergency exits and the hence long distances to be covered to the portals, this could be dangerous. Orientation in a fire is also difficult because these escape routes are not marked by evacuation lighting.

9.3 Check list

A checklist that was prepared by the traffic experts at ADAC and DMT and which is revised every year with the experts from the member European automobile clubs served as an objective foundation for testing. The checklist is also based on the high standards for road tunnels in Germany, Austria, Switzerland, France and the UK, as well as on the EU Directive on minimum safety standards for tunnels in the Trans-European Transport Network.

<u>The checklist is broken down into eight categories:</u>

Tunnel system Weighting: 14 percent

* Number of tubes
* Brightness of tunnel walls
* Width and layout of traffic lanes
* Geometry and layout of emergency lanes / lay-bys and emergency walkways
* Additional measures: Portal design, road surface, tunnel route

• Lighting and power supply Weighting: 8 percent

* Lighting throughout and adaptation zones
* Power and emergency power supply

• Traffic and traffic surveillance Weighting: 17 percent

* Congestion in the tunnel * Restrictions on and/or registration of vehicles carrying hazardous goods * Measures to close the tunnel: traffic lights, barriers, information displays * Traffic signs * Traffic management and control: traffic lights, variable traffic signs, signs * Visual guidance equipment * Video surveillance * Automatic traffic recording and detection of congestion and incidents * Tunnel control centre * Additional measures: for instance for heavy goods vehicles and automatic recognition of hazardous goods transports, height checks, speed limits, monitoring the distance between vehicles and speed **• Communication Weighting: 11 percent** * Traffic radio * Loudspeakers * Emergency phones: distance, marking, insulation against traffic noise, functions * Tunnel radio **• Escape and rescue routes Weighting: 13 percent** * Evacuation lighting and escape route signs in the tunnel * Preventing smoke from penetrating external escape routes, fire resistant doors * Distance between emergency exits and marking * External access and access for rescue services * Additional measures: special lighting for emergency exits, signs showing what to do, barrier-free emergency exits **• Fire protection Weighting: 18 percent** * Fire protection on the tunnel structure * Fire resistance of cables * Drainage system for draining flammable and toxic liquids * Fire alarm systems: automatic/manual * Extinguishing systems: arrangement, signs, function * Time to reach the tunnel, fire brigade training and equipment * Capacity and efficiency of automatic extinguishing systems **• Ventilation Weighting: 11 percent** * Normal mode to thin out vehicle emissions * Control of the longitudinal flow in the tunnel and consideration of this in ventilation control * Temperature stability of facilities and equipment * Special fire programmes * Proof of correct functioning in fire trials and by flow measurements *Longitudinal ventilation: airflow speed, length of the ventilation section, airflow in the direction of traffic, reversible fans. * Transverse / semi-transverse ventilation: extraction volume flow, longitudinal flow control, opening / closing the exhaust air outlets can be controlled **• Emergency management Weighting: 8 percent** * Regular training for tunnel control centre staff * Maintenance plan * Emergency response plans * Automatic linking of emergency systems * Measures in the case of accident or fire * Regular emergency drills

Source: http://www.eurotestmobility.com

10 Appendix: Traffic prognosis

AADT Annual Average Daily Traffic

The traffic was studied in [4] Vegargerðin Hvalfjarðargöng, Umferðarúttekt – Umferðarspá. This report was based on the traffic development from 1999 – 2005, and it stated among others: ”Traffic through the Hvalfjörður tunnel has grown more rapidly than forecasted in its planning stages.”

The traffic development from 1999 – 2005 is shown in Table 10.1

Year	AADT
1999	2938
2000	3241
2001	3557
2002	3660
2003	3846
2004	4103
2005	4715

Table 10.1 Traffic registration in the years 1999 - 2005

The report established a traffic forecast: ”Three different traffic forecasts for traffic growth from 2005 to 2030 were developed.

A base (lower boundary) forecast assumes that a population forecast for Vesturland will come true and trip rate and trip purpose will be in accordance with the survey done in 2002. With these assumptions annual traffic growth will be from 1.8 to 2.7%. AADT will increase by 66% from 2005 to 2030.

For a mid-level forecast it is assumed that population growth in Vesturland will be in accordance with the population forecast. An increase in rate of trips between Vesturland and the Reykjavik area is assumed and a major development in Grundartangi industrial area as well. Forecasted annual traffic growth will be from 4.3 to 5.2% from 2005 to 2030.

An upper boundary forecast is based on similar assumptions as the mid-level forecast. It assumes that rate of trips between Vesturland and the Reykjavik area will increase more and faster, more development will occur in Grundartangi peninsula and increased traffic growth on other links. Annual traffic growth from 2005 to 2030 is from 6.6 to 7.8%. Traffic grows more rapidly than predicted in the moderate forecast, in 2016 it will be twice the AADT in 2005.”

In the meanwhile the development from 2005 to 2012 has been more modest than foreseen in the study in 2006. The actual traffic registered by Spölur (ref www.spolur.is) is shown in Table 10.2.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Dec	AADT
2008	4006	4492	5027	5154	5748	6814	7700	7216	5474	4631	4589	4130	5496
2009	4059	4384	4324	5353	5689	7105	8032	7060	5390	4634	4561	4096	5401
2010	3941	4134	4648	4957	5703	6921	7905	6934	5448	4998	4320	4167	5349
2011	3708	4020	3939	4818	5065	6751	7873	6971	5425	4618	4182	3649	5091
2012	3227	4083	4145	4941	5218	6711	7400	7054	5237	4571	3849	3855	5042

Table 10.2 Average Monthly Daily Traffic and AADT for the years 2008- 2012.

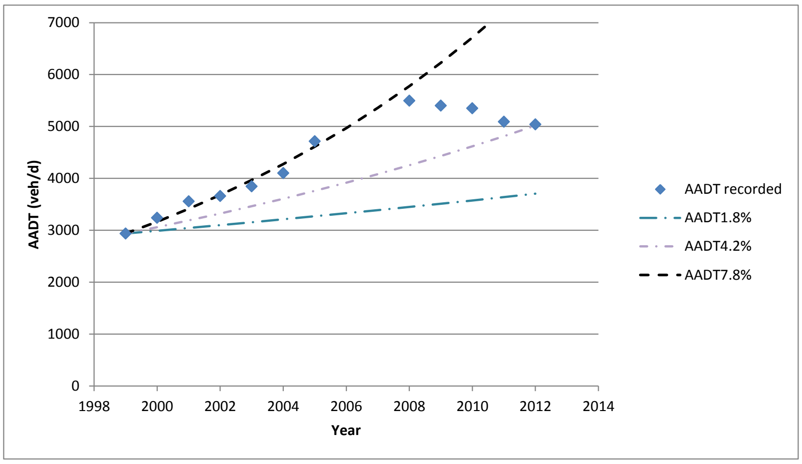


Figure 10.1 Recorded AADT and original forecasts from 2006 [4].

The forecasts made in 2006 did not foresee the reduced traffic in the years 2008 – 2012. Generally, the traffic development follows the economic development, and a reduction of traffic is in line with the transition that Iceland has undergone in the years 2008 – 2012. It could not have been expected that the traffic prognosis would foresee this development.

The development in the entire time range from 1999 to 2012 gives an average traffic growth of 4.2%, which is a significant growth. In West-European Countries the economic growth (and the growth in traffic) is normally in the order of 2%. However, an assumption of 2% growth in the future seems to give a quite low value given the fact that the average growth has been over 4% including a 5 year long reset.

In the risk studies it may be relevant to consider a ranger of traffic growth, e.g. minimum growth 1.8%, medium growth 2.4%, maximum growth 4.2%. An extreme case of 7.8% growth will not be pursued. Hereby the AADT shown in Table 10.3 and illustrated in Figure 10.2 can be calculated

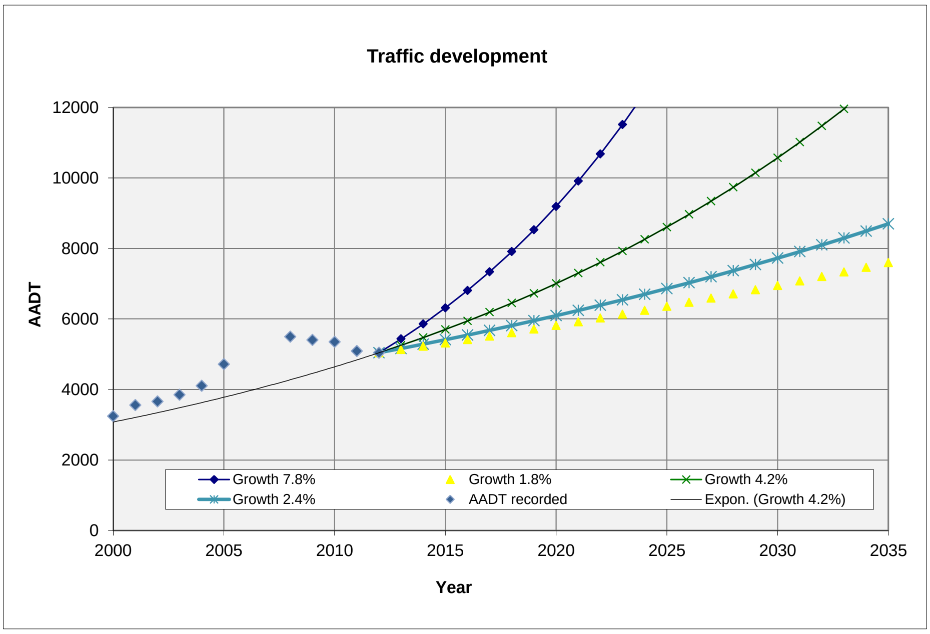


Figure 10.2 Possible traffic forecast models

Hvalfjordur Tunnel	2013	2023	2033
AADT 1.8% growth	5132 veh/day	6025 veh/day	7332 veh/day
AADT 2.4% growth	5162 veh/day	6366 veh/day	8230 veh/day
AADT 4.2% growth	5253 veh/day	7607 veh/day	11960 veh/day
AADT 7.8% growth	5434 veh/day	10683 veh/day	24407 veh/day

Table 10.3 Forecasts for the AADT in Hvalfjördur tunnel based on four growth rates (the growth rate 7.8% is only shown for information).

HGV percentage

Based on the registration in 2004 the percentage of heavy goods vehicles (HGVs) was 6.5%.

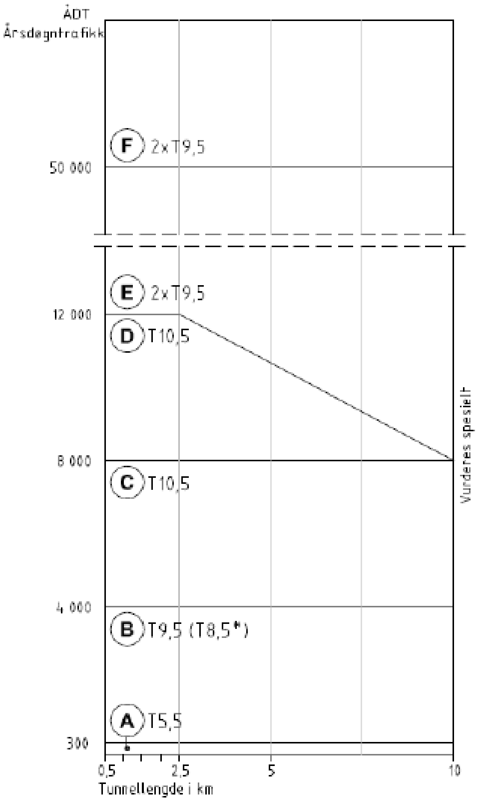
It shall be noted that the share of HGV traffic is lower at times with high hourly traffic (i.e. the HGV traffic is more evenly distributed over the day, week and year than the traffic with light vehicles).

For the present risk analysis it has been assumed, however, that the percentage of HGVs will be 6.5% in 2013 and 2033.

11 Appendix: Comparison with requirements in guideline HB021

11.1 Tunnel class

The requirements are relative to the tunnel class, which in HB021(2010) is specified as follows:



Figur 11.1 Tunnel classes according to HB021.

The Hvalfjörður tunnel has today around AADT = 5100 veh/d. In HB021 is specified:

"Tunnelklasse skal velges ut fra den trafikkmengde som kan forventes 20 år, ÅDT (20), etter at tunnelen er åpnet for trafikk."

AADT in 2033 has been estimated to 8230 veh/d.

In addition HB021(2010), specifies:

4.4 *Ved ujevn trafikkmengde over døgnet eller over året, eller hvis det er stor usikkerhet i beregningsgrunnlaget for ÅDT(20), anbefales tunnelklasse valgt ut fra en spesiell vurdering. En slik spesiell vurdering for valg av tunnelklasse skal være basert på risikoanalyse…. Høy tungtrafikkandel eller større døgnvariasjoner kan begrunne en annen standard for tunnel og veg sett under ett.*

The high traffic during summer and weekend could tend to give a higher tunnel class. However, the relevant tunnel class for Hvalfjördur would be class C now and during the end of the considered period of time the tunnel class would be class D.

11.1.1 Geometric Requirements

In the following the geometrical requirements of HB021 (2010) are compared with the tunnel condition (taking the traffic in 2033 as basis for the evaluations) (The original text in Norwegian language has not been translated)

Ref. HB021	**HB021 requirements** *"citat"*	
4.1	*Ved geometrisk oppgradering av eksisterende tunneler bør fri høyde legges på minimum 4,2 m og kjørefeltbredder følge standard krav for nye tunneler. Dette vurderes spesielt i hvert tilfelle ut fra stedlige forhold samt nytte/kostnad for tiltakene.*	Ok
4.2.2	*Krav til stoppsikt vil bestemme minste horisontalkurve.... Sammenhengen mellom horisontalkurveradius (R), stoppsikt (LS) og avstand fra bilførerens øye til tunnelveggen (B) er gitt ved formelen $R = LS^2/8B$.*	Ok
	Vdim= 70 km/t → LS = 87 m og B = 3.50 m (T9.0) giver R min= $87^2/(8*3.50) = 270$m	Ok
4.2.3	*" Med unntak for undersjøiske tunneler skal ikke veg i tunnel bygges med mer enn 5 % stigning."*	Gradient 7% and 8.1%
4.2.4	*" Veg i tunnel unntas fra forbikjøringskravene i håndbok 017. Det kan likevel være aktuelt å legge til rette for forbikjøring i tunnel. Forbikjøringsmuligheter sikres ved å sørge for at sikten er tilstrekkelig eller ved å anlegge ekstra kjørefelt, ... I tunneler hvor forbikjøringsmuligheter sikres med tilstrekkelig sikt, anbefales det å benytte meget slake kurve*	Overtaking is regulated by long lines indicating that "caution shall be taken" by overtaking. At sections with two lanes in the direction overtaking is allowed.
4.3.1	*"Det skal være en overgangssone mellom skulder-bredden på veg i dagen og skulderbredden på ve-gen i tunnel.Overgangssonen skal være 100 m lang og være utformet som en lineær overgang. Over-gangssonen skal være avsluttet 200 m før tunnel-portalen."*	No transition zone but instead a section with crash barriers
4.3.2	*For å eliminere trafikkfare ved utrasing av blokker eller stein, ved snøskred, nedfallende is eller liknende og for å hindre at vann renner ut over påhugget og ned i vegbanen, skal det bygges portaler i tunnelmunningene.* *I tillegg skal det sikres at forskjæringen inn mot portalen har tilstrekkelig bredde ut fra plassbehov ved mulig nedfall av is, snø eller stein...*	Not a problem in Hvalfjörður
4.4	Tunnelklasse B: min T9.5 Tunnelklasse C: min T10.5 Tunnelklasse D: min T10.5 Tunnelklasse E: min 2 x T9.5	The tunnel cross section is too narrow for tunnel class C and D (and also for class B)
4.5.1	*T13 skal brukes der det er behov for tre kjørefelt i tunnelklasse B.* (og E og F?)	The tunnel cross section (T11) is too narrow for three lanes
4.5.1	Kjørefeltbredder ÅDT > 1500: 3.5 m	The lanes are 3.00 m – 3.25 m – i.e. too narrow
4.4	*Ved ujevn trafikkmengde over døgnet eller over året, eller hvis det er stor usikkerhet i beregningsgrunnlaget for ÅDT(20), anbefales tunnelklasse valgt ut fra en spesiell vurdering. En slik spesiell vurdering for valg av tunnelklasse skal være basert på risikoanalyse.*	Ok, It can be relevant to use tunnel class D as reference before AADT = 8000 veh/d has been reached
4.4	*Høy tungtrafikkandel eller større døgnvariasjoner kan begrunne en annen standard for tunnel og veg sett under ett.*	The HGV share is not particularly high
4.51	*"Kravet på fri høyde i tunneler er 4.6 m".*	Ok
4.51	*"Minimum høyde til teknisk utrustning skal være 4.8 m..."*	Ok ?
4.5.5	*Gang- og sykkelveg føres ... i samme tunnel skilt med*	Pedestrians and bicyclists are prohibited in the tunnel

	rekkverk fra biltrafikken,...	
4.5.6	*"Opphøyd del av skulder skal utføres med kantstein og med asfalt eller betongdekke, med minimum 5 % fall mot kjørebanen (figur 4.22). Kantstein skal være lav og ikke-avvisende og plasseres 0,25 m fra kjørebanekant"*	The shoulders are not conform. New shoulders are presently being constructed.
4.5.7	*I tunnelens lengderetning monteres enten veggelementer av betong eller føringskant av betong*	No guides and no concrete elements
4.6.1	*" Normalavstand for nisjer fremgår av ... De gitte avstander er omtrentlige mål. Plassering skal tilpasses lokale forhold som bergforhold og geometri. Toleranse i plassering bør være innenfor ± 50 m" ... "Tunnelklasse C Normalafstand 750 m, Tunnelklasse D Normalafstand 500 m per retning. Tunnelklasse E, Normalavstand havarinisje 500 m, (Angitt avstand gjelder for hvert tunnelløp)»*	*Distances between lay-bys are ok*
4.6.1	*Havarinisjer utformes som vist på figur 4.23*	*The design of the lay-bys is not in accordance with the most recent requirements in HB021(2010) – the wall shall slope 1:10 by change of width.*
4.6.1	Snunisjer: Tunnelklasse B, Normalafstand 2000 m, Tunnelklasse C, Normalafstand 1500 m, …Snunisjer bygges i tunneler med lengde over 2 x normalavstanden for snunisjer i aktuelle klassen	Ok
4.6.2	*Teknisk rom skal plasseres i egen nisje med tett vegg mot trafikkrommet.*	Ok
4.6.3	*Nødstasjoner mellom havarinisjene plasseres i skap.*	Ok
4.6.3	*Skapene kan plasseres på føringskant av betong eller innfelles i tunnelveggen. Av trafikksikkerhets-hensyn skal framkant av skap være utenfor normal-profil*	Ok The cabinets are not completely embedded in the wall
5.2.1	*(Tabell 5.1) Gangbare tverrforbindelser, hver 250 m i klasse E og F*	No cross sections.
5.2.1	*(Tabell 5.1) Kjørefeltsignaler bør vurderes*	Could be considered
4.8.1	*Kryss i tunnel skal unngås.*	Ok
4.8.2	*Når vegen gjennom tunnelen er forkjørsveg, skal plankryss … ikke anlegges nærmere tunnelåpningen enn 2 x stoppsikt (LS).*	Ok
4.8.2	*Planskilt kryss ved tunnelåpning skal ikke ha kortere lengde på fartsendringsfeltene enn angitt i håndbok 017.*	Ok
4.7	*I tunneler i tunnelklasse D (og eventuelt C) som bygges med nødutganger fra tunnelen til det fri (se punkt 5.1) eller rømningstunnel med gangbare tverrforbindelser til hovedløpet, skal avstanden mellom utgangene/tverrforbindelsene ikke overstige 500 m.*	No exits
5.1	*Tunneler i tunnelklasse D (antall kjøretøy pr kjørefelt over 4 000) og tunneler i tunnelklasse C som er lengre enn 10 km, skal anlegges med nødutganger / rømningstunnel (se punkt 4.7). For tunneler i tunnelklasse C som erkortere enn 10 km skal det utføres en risikoanalyse for å avgjøre om tilsvarende eller bedre sikkerhet kan oppnåsmed alternative tiltak.*	The tunnel is required to have exits in tunnel class D.

11.1.2 Sign and signalling

Ref. HB021	**HB021 requirements Skiltning uden for tunnel:**	
6.2.1	Tunnelnavn (727.4/eller blot navn)	Ok
6.2.1	Advarselsskilt tunnel (122)	-
6.2.1	Hastighedsbegrænsningsskilt	Yes, 70 km/t

6.2.1	Forbikjøringsforbud / Forbikjøringsforbud for lastebil	Yes all vehicles
6.2.1	Forbud for syklende / gående	Yes also for horses
6.2.1	Brat bakke for hældning > 5%	Yes
6.2.1	Radiostationsfrekvens	
6.2.1	Rødt stopblinksignal	Yes
6.2.1	Bom med lys	Yes
6.2.1	Skilt for nødtelefon og brandslukker	To be improved
6.2.1	Variable skilte overvejes	-
6.2.1	Skilt "høydegrense"	-
6.2.2	**Skilte mm. Inde i tunnelen**	
6.2.2	Skiltene skal være belyst, evt. vha. indvendig belysning.	Ok
6.2.2	*Fri høyde under sideplasserte skilt skal være minimum 2,0 m over skulder.*	Ok?
6.2.2	Hastighedsbegrænsningsskilte	Ok
6.2.2	Radiostation og frekvens for hver 500 m	Ok
6.2.2	Skilte for havarinisjer	Ok
6.2.2	Skilt for nødtelefon og brandslukker	Ok
6.2.2 5.2.1	Avstandsmarkering til tunnelåpning for tunneler over 3 km	-
6.2.2	Nødudgangsskilt	No exits
6.2.2	Etterlysende rømningsskilt til nærmeste nødut-gang.	Not considered applicable, because no special emergency exits exist. Only signs on emergency cabinets, and telephone booths per 125 m
6.2.2	Skiltes virkning på (belysning) og ventilation skal vurderes specielt	Assumed ok
6.2.2	Variable skilte kan overvejes	-
6.3	Tunneler skal være utstyrt med signal nr. 1094 Rødt stoppblinksignal foran tunnelåpningene	Ok
6.4	Visuel føring. Kantlinier skal brukes til afgrens-ning av kørebanen mod skulder. Profilerte linjer	Ok
6.4	Adskillelse af kørebaner lang midtlinien (enkelt – eller dobbelt linje) med lett synlige midler. Profi-lerte linjer	Ok
6.4	Vegbane reflektorer bør vurderes, især ved lavt belysningsnivå.	Can be considered
6.4	Profilert oppmerkning ...i tunnel bør føres minst 100 m ud av tunnelen.	Antages

11.1.3 Safety equipment

In the following the safety requirements of HB021 (2010) are compared with the tunnel condition (taking the traffic in 2033 as basis for the evaluations) (The original text in Norwegian language has not been translated)

Ref. HB021	HB021 requirements	
5.2.1	Nødstrømsanlæg	Ok
5.2.1	Ledelys/rømningslys per 62.5 m	Missing
5.2.1	Nødstasjon per 125 m (opgradering 250 m)	Ok
4.6.1	*Nødstasjon i tilknytning til havarinisjer monteres i støvtett kiosk med innvendig belysning.*	Ok
4.6.1	*Nødstasjoner mellom havarinisjene plasseres i skap.*	Ok
5.2.2.3	Hver nødstasjon skal inneholde en nødtelefon og to brannslokkere.	Ok
5.2.2.3	Nødtelefon skal være av en type som gir ringesignal når røret løftes av. Telefonen skal gi kontakt med bemannet sentral, fortrinnsvis vegtrafikksentral.	Ok connection to the emergency central
5.2.1	Fjernstyrte bommer for stengning (kan overvejes)	Ok
5.2.1/	Radio- og kringkastningsanlæg	Ok, TETRA communication system available for fire brigade and

5.2.3	Tunneleier har ansvar for å etablere radioanlegg for videreformidling av nødkommunikasjon og kringkasting i alle tunneler lengre enn 500 m.	police.
	Radioindsnak	Ok
5.2.1	Mobiltelefon (kan overvejes)	Ok
5.2.1/ 5.2.2.7	Høydehinder ... bør være deformerbart og ha en ekstra sikring som hindrer nedfall ved påkjørsel. Høydehinder kan sløyfes dersom bruer eller andre konstruksjoner har den nødvendige avvisende effekt...	Ok

11.1.4 Fire and dangerous goods

Ref. HB021	**HB021 requirements**	
5.2.1 5.2.2.4	*Slokkevann. Alternative løsninger er: etablering av egne kummer (ca. 6 m^3) i tilknytning til drenssystemet…, tankvogn med tilstrekkelig kapasitet (minimum 6 m^3), slokkevannsreservoar ved lavbrekk*	Ok
5.4.2	*For brannsikring av vann- og frostsikring henvises det til håndbok 163 Vann- og frostsikring i tunneler.*	Ok
5.4.2	*5.4.2 Brannmotstand. Krav til konstruksjoner Dimensjonerende brann og krav til konstruksjoners brannmotstand er...Tunnelklasse E: 50MW, 60 minutter HC brandkurve, Tunnelklasse F: 100 MW, 60 minutter HC brandkurve.*	Investigation can be recommended, assumed to be ok.
5.5	*I Norge faller de fleste tunnelene normalt i restriksjonsklasse a. Dersom det transporteres særlig farlig gods i tunnelen vil en risikoanalyse kunne belyse behovet for å innføre andre restriksjonsklasser.*	Restrictions for dangerous goods in peak hours

11.1.5 Other requirements

Ref. HB021	**HB021 requirements**	
5.6	*For alle tunneler lengre enn 500 m har tunneleier ansvar for at der utarbeides en beredskapsplan.*	Ok
8.2	*Avstanden mellom kummer på samme ledning bør ikke overstige 80 m.*	Ok
8.4	*På ledning for oppsamling av overflatevann og vann fra vask av tunnelen skal det monteres sandfang med største avstand 80 m.*	Ok
8.4	*Det skal legges spesiell vekt på at eventuell lekkasje av brannfarlige væsker ikke skal spre seg til andre deler avtunnelrommet.*	Ok
8.6	*Størrelse og antall pumpestasjoner skal bestemmes ut fra stedlige forhold, totaltenergiforbruk, drift og vedlikehold, sikkerhets- og beredskapsnivå. Xxx .*	Assumed ok
10.2	*"... strømforsyning sikres ved uavhengig forsyning fra begge tunnelmunninger som kobles sammen..."*	?
10.3.1	*Belysning. Generelt. Vegtunneler med lengde over 100 m skal ha belysning.*	Ok
10.3.3.1	*For ÅDT(10) > 8000 skal anvendes adapsjonsluminans: 5%.*	Lighting is ok until ÅDT surpasses 8000 veh/d
10.3.3.1	*For ÅDT(10) > 8000 ska indre sone dag/nat luminansen være 4.0 cd/m2 /2.0 cd/m2*	
10.4.1	*Det skal monteres ventilasjonsanlegg i tunneler med lengde over 1000 m når ÅDT er over 1000 kjøretøy/døgn.*	Ok
10.4.1	*Luftkvaliteten skal overvåkes med måleutstyr for*	Ok

	CO og NO_2 (eller eventuelt NO).	
10.4.4	*Krav til brannventilasjon: For Tunnelklasse E og tunnellængde over 1 km: 50 MW, ISO 835 60 min og minimum lufthastighet 3.5 m/s. Tunnelklasse D og tunnellængde over 1 km:100 MW, minimum lufthastighet 4.5 m/s, tunnelklasse C og tunnellængde over 1 km: 50 MW*	In tunnel class C the ventilation system shall be designed for 50 MW fire. In tunnel class D the system shall be designed for 100 MW fire.
10.4.4	*Tabell 10.5 inneholder krav til minimum brannventilasjon i tunneler med stigning under 2 %.*	-
10.4.4	*Ved stigning over 2 % skal nødvendig luftha-stighet beregnes.*	Ok

12 Appendix: Modelling of characteristics

12.1 Introduction

In the following some of the models used for the detailed risk analysis are presented. Some models are part of the quantitative risk analysis [39], other characteristics will have to be modelled separately.

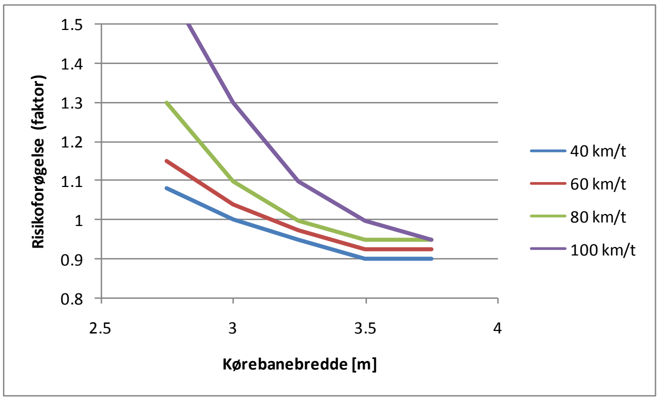
The modelling of characteristics is carried out in order to determine the number of accidents, injuries and fatalities per year and per vehicle-km. The accidents are considered in three groups: traffic accidents, fires and events with dangerous goods.

In the following an increase of the risk respectively a reduction of risk is discussed for the various characteristics – these terms are relative to an ”average” tunnel modelled based on statistics from Norway and adapted to Icelandic conditions.

12.2 Geometry

12.2.1 Cross section

The width of the lane influences the risk of accidents. A model for this relation has been established and is shown below. The risk has some influence from the speed as well.



Figur 12.1 Increased risk at lane widths depending on speed. .

12.2.2 Gradienter

A model has been proposed for gradients. A model exists both for the relation with respect to accidents and another with respect to fires. An accident modification factor, F_α is calculated as function of the change in gradient $\Delta\alpha$ (i %). The relation is calculated in Table 12.1, with an assumed reference gradient of α_0 (2%)

$$F_\alpha = e^{0.081 \cdot \Delta\alpha}$$

Gradient	F_{α}
0%	0.85
2%	1
4%	1.18
6%	1.38
8%	1.63
10%	1.91

Table 12.1 Accident modification factor dependent on gradient

At a gradient of 7.2% the risk of accidents is increased by 50%, and with 8% it is increased 63%.

12.2.3 Horizontal radiuses

It has been observed that the risk of accidents is higher at curves. Based on the observations a relationship has been established. The accident increase factor has been integrated in the quantitative risk analyses.

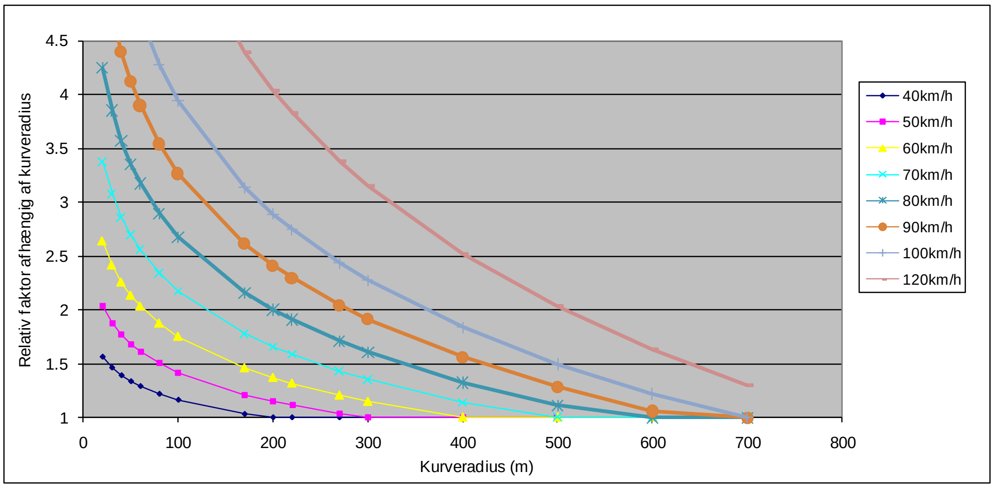


Figure 12.2 Modelling of the risk increase dependent of the curve radius and speed.

12.2.4 Exits

Based on models from earlier projects a relationship between (fire-) risk and the distances between exits exist. This relationship is integrated in the quantitative risk analyses and documented in [39].

12.2.5 Tunnel portals

The risk is generally higher at portals This is generally integrated in the model for the quantitative risk analyses[39].

12.3 Traffic and related issues

12.3.1 Speed

Speed is of major importance for the safety in the tunnel.

The frequency of accidents and their consequences is dependent of the average speed . The following relationship has been established by Nilsson (Nilsson, 1984/OECD153) [19].

It is assumed that the reference speed for tunnels in general is 80 km/h. The general accidents statistics are assumed to correspond to this speed. If the speed is reduced the frequency of accident will reduce and also the consequences will reduce.

Accidents (y)	Casualties (z)
Fatal accidents	Fatalities
$y_1 = \left(\frac{v_1}{v_0}\right)^4 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^4 y_0 + \left(\frac{v_1}{v_0}\right)^8 (z_0 - y_0)$
Fatal and severe accidents	Fatalities and severely injured
$y_1 = \left(\frac{v_1}{v_0}\right)^3 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^3 y_0 + \left(\frac{v_1}{v_0}\right)^6 (z_0 - y_0)$
All injury accidents	All injured (fatalities included)
$y_1 = \left(\frac{v_1}{v_0}\right)^2 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^2 y_0 + \left(\frac{v_1}{v_0}\right)^4 (z_0 - y_0)$

Figure 12.3 The relationship between speed and traffic safety ref. Nilsson i [19]

The relationships between fatality risk and speed is illustrated in *Figure 12.4*.. Similar relationships can be established for injuries and accidents.

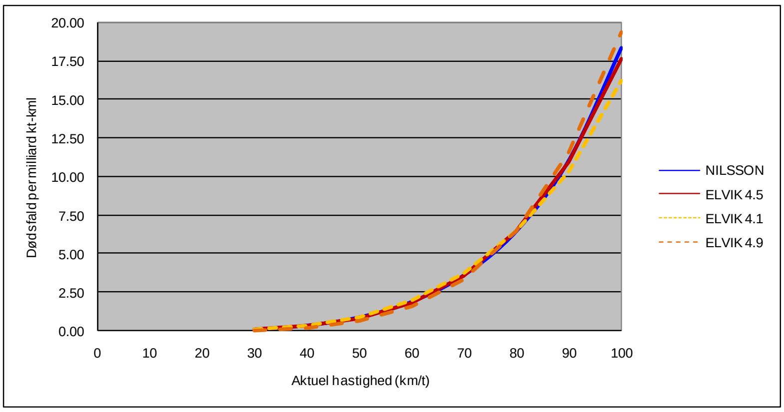


Figure 12.4 Fatality risk dependent of speed (reference speed 80 km/h) reference Nilsson and Elvik([28] and [29]).

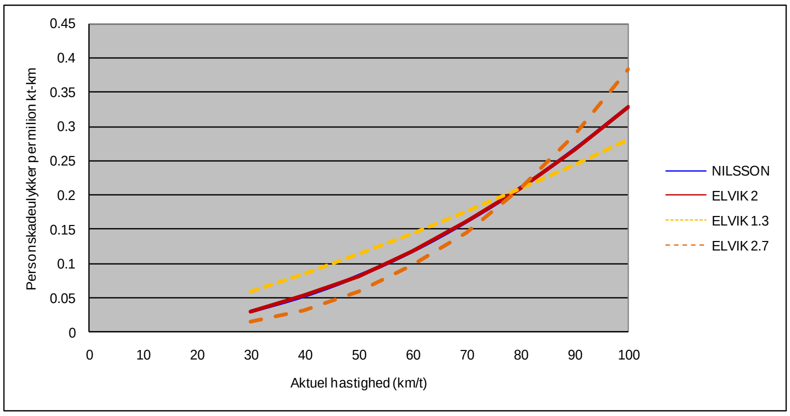


Figure 12.5Injury risk dependent of speed (reference speed 80 km/h) reference Nilsson and Elvik ([28] og [29]).

12.3.2 Traffic volume

The traffic volume influence the frequency of accidents. Measured in accidents per vehicle km the relationship has been established as shown in the figure below. This relationship between AADT and accident modification factor is integrated in the quantitative risk analysis [39].

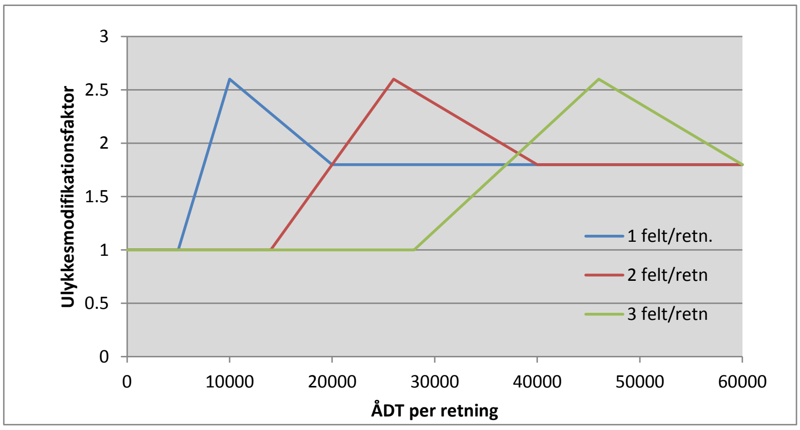


Figure 12.6 Modelling of the influence of AADT on the accident modification factor.

12.3.3 HGV percentage

It has been observed that HGVs has a higher frequency of accidents than light vehicles [16]. In addition the fire frequency is higher for HGVs and the consequences are potentially higher for fires in HGVs.

The influence of HGV traffic is taken into account in the quantitative risk analysis.

12.3.4 Dangerous goods transports

The risk of dangerous goods events is calculated as part of the quantitative risk analyses [39].

12.4 Tunnel equipment etc.

12.4.1 Light in the tunnel interior

For the luminance in the tunnel a model based on expert judgement is used as part of the quantitative risk analyses [39] Figure 12.7.

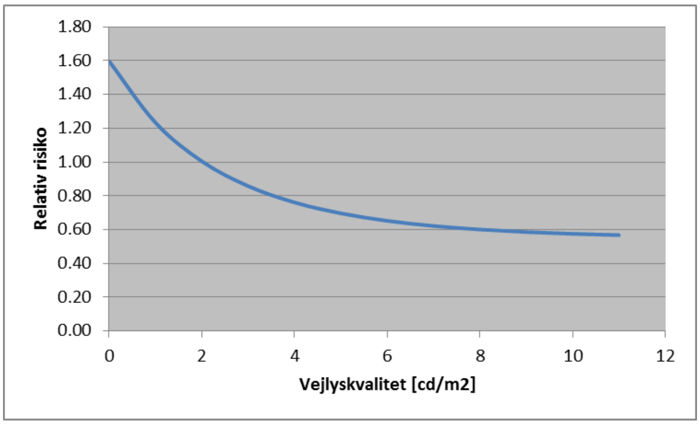


Figure 12.7 Relationship between luminance and risk.

Luminance [cd/m2]	F_l
0	1.6
0.5	1.4
2	1
4	0.76
6	0.65
8	0.60
10	0.58

Table 12.2 Accident modification factor dependent on the luminance level (tunnel interior).

The above relationship has been established in connection with the project “Best practice for risk analyses” [39]. The relationship is based on expert judgement and has been used both in Norway and Switzerland [40], [41].

12.4.2 Communication

In case of events in the tunnel it is difficult to communicate with the tunnel users. The available means of communication are:

- Emergency telephones. Tunnel users can report accidents and get a message back with advice on how to react to the situation.
- Mobile phones can be used in the same way as emergency phones. In this situation no automatic localisation of the call will be available
- The tunnel operator can close the tunnel by using the red lights and the barriers

In addition the fire brigade and the police can instruct the road/tunnel user when they arrive to the tunnel.

12.4.3 Fire ventilation

The ventilation system is one of the important safety systems in a tunnel. If the system is insufficient or out of operation the consequences of a fire can be significantly more severe than for a well-designed, functioning system.

Based on previous project and expert knowledge in the development of the best practice for risk analysis the model for the influence of ventilation can be taken into account. For a more detailed evaluation of ventilation , proper ventilation studies and smoke dispersal model can be used.

12.4.4 Fire water

For fire fighting the fire brigade shall have sufficient water available in the tunnel. This can be arranges as hydrants or the fire brigade can bring water in water tanks to the fire. The equipment and the procedures for this shall be discussed with the local fire brigade.

13 Appendix: Reference tunnel

In order to determine the risk in the tunnel the tunnel risk analysis programme TRANSIT [39] has been used. In the present appendix the risk is calculated for the so-called reference tunnel . The reference tunnel corresponds to the actual tunnel and has the same length and traffic, but is completely without special characteristics and deviations from the requirements of the guideline (here HB021 (2010)). In the actual case the reference is a tunnel in tunnel class D.

The tunnel is divided into sections as described below Table 13.1

North bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
	S Portal							
H1n		1590	50	2000	-2	1	4.25	4115
H2n		1640	50	2000	-2	1	4.25	4115
H3n		1690	100	2000	-2	1	4.25	4115
H4n		1790	360	2000	-2	1	4.25	4115
H5n		2150	320	2000	-2	1	4.25	4115
H6n		2470	240	2000	-2	1	4.25	4115
H7n		2710	2290	2000	-2	1	4.25	4115
H8n		5000	110	2000	-2	1	4.25	4115
H9n		5110	90	2000	-2	1	4.25	4115
H10n		5200	200	2000	2	1	4.25	4115
H11n		5400	250	2000	2	1	4.25	4115
H12n		5650	400	2000	2	1	4.25	4115
H13n		6050	360	2000	2	1	4.25	4115
H14n		6410	490	2000	2	1	4.25	4115
H15n		6900	350	2000	2	1	4.25	4115
H16n		7250	100	2000	2	1	4.25	4115
H17n		7350	50	2000	2	1	4.25	4115
H18n	N Portal	7400	50	2000	2	1	4.25	4115

South bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
	S Portal							
H1s		1590	50	2000	2	1	4.25	4115
H2s		1640	50	2000	2	1	4.25	4115
H3s		1690	100	2000	2	1	4.25	4115
H4s		1790	360	2000	2	1	4.25	4115
H5s		2150	320	2000	2	1	4.25	4115
H6s		2470	240	2000	2	1	4.25	4115
H7s		2710	2290	2000	2	1	4.25	4115
H8s		5000	110	2000	2	1	4.25	4115
H9s		5110	90	2000	2	1	4.25	4115
H10s		5200	200	2000	-2	1	4.25	4115
H11s		5400	250	2000	-2	1	4.25	4115
H12s		5650	400	2000	-2	1	4.25	4115
H13s		6050	360	2000	-2	1	4.25	4115
H14s		6410	490	2000	-2	1	4.25	4115
H15s		6900	350	2000	-2	1	4.25	4115
H16s		7250	100	2000	-2	1	4.25	4115
H17s		7350	50	2000	-2	1	4.25	4115
H18s	N Portal	7400	50	2000	-2	1	4.25	4115

Table 13.1 The tunnel geometry and traffic for the reference tunnel. The tunnel is for the description divided into 18 sections in each direction. Traffic AADT is given for the year 2033 and covers each direction.

The tunnel cross section corresponds 1 tube with T10.5 with one lane in each direction (equivalent lane width of 4.25 m). The gradient is 2%. The share of heavy goods is assumed 10% and of which 3% is dangerous goods.

The reference tunnel is calculated for 2013 and 2033. The difference is the AADT and luminance. AADT is 8230 veh/d for 2033 and 5160 veh/d for 2013; the luminance is 4 cd/m^2 for 2033 and 2 cd/m^2 for 2013.

The result is summarised in the following:

	Fatalities / year	Injuries/year	Events/year	
Accidents	0.0713	1.392	0.909	
Fires	0.0039	0.057	0.386	
Dangerous goods	0.0000	0.000	0.000	
Total	0.0752	1.449	1.296	
Traffic	11.04		Million veh-km/yr	
Accident rate	0.082		Per Million veh-km	
Fire rate	0.035		Per Million veh-km	
Fatality rate	6.82		Per Billion veh-km	

Table 13.1 Reference tunnel 2013: Personal risk and expected number of accidents and fires for the reference tunnel.

	Fatalities / year	Injuries/year	Events/year	
Accidents	0.0929	1.765	1.171	
Fires	0.0081	0.077	0.604	
Dangerous goods	0.0002	0.001	0.000	
Total	0.1011	1.843	1.775	
Traffic	17.60		Million veh-km/yr	
Accident rate	0.067		Per Million veh-km	
Fire rate	0.034		Per Million veh-km	
Fatality rate	5.74		Per Billion veh-km	

Table 13.2 Reference tunnel 2033: Personal risk and expected number of accidents and fires for the reference tunnel.

As it appears the risk of the reference tunnel is below the specified upper limit of the risk (see section 3).