Vegagerðin

Hvalfjörður Road Tunnel II

Contribution to Risk Analysis of alternatives for extension

January 2020

HOJ Consulting GmbH

Ballyweg 33
CH-6440 Brunnen
Switzerland

www.hoj.ch

Vegagerðin

Hvalfjörður Road Tunnel II

Contribution to Risk Analysis of alternatives for extension

January 2020

Report No.	H-IS-008
Revision	A
Date	3 January 2020
Prepared	Niels Peter Høj

List of Contents

1 Introduction

Client	Vegagerðin
Tunnels	Hvalfjörður Tunnel II
Status	One tube: In operation, second tube in planning.
Length	Present tunnel tube: 5770 m, second tube: 6125 m – 7540 m
Speed limit	70 km/h
Road Traffic volume	15’000 veh / day (in ~2040)

Table 1.1 Key figures concerning the tunnel

The existing Hvalfjörður Tunnel has been in operation for more than 20 years. Since then the traffic has increased significantly with in average 4.9% per year. The AADT for 2019 is estimated at 7850 veh/d, with an daily average traffic in the summer months of 9800 veh/d. For this reason and for improving the safety it is being investigated how the tunnel can be extended.

The safety in the existing tube of the Hvalfjörður tunnel was investigated and analysed in a risk analysis of 2013 (updated in 2017). As a base line for the evaluation of alternatives, the risk analyses of the existing tube is updated with the new traffic figures. The alternatives are analysed with the same methods, and with more detailed models for the smoke spread, ventilation and evacuation and the it is evaluated which alternative is the most feasible.

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 [20], [21], [22] and [23].

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 existing tunnel in North of Reykjavik across the Hvalfjörður

The existing tunnel is located North of Reykjavík as part of Highway No. 1. The tunnel crosses the Hvalfjörður and with the opening of the tunnel a 42 - 60 km long detour around the fjord was avoided. The tunnel is a toll paid section and a toll booth is located outside the northern portal collecting payment from both the northbound and the southbound traffic. For reference the existing tunnel is studied in Appendix chapter 10 with the same traffic as used for the extension alternatives.

1.1.1 The extension alternatives

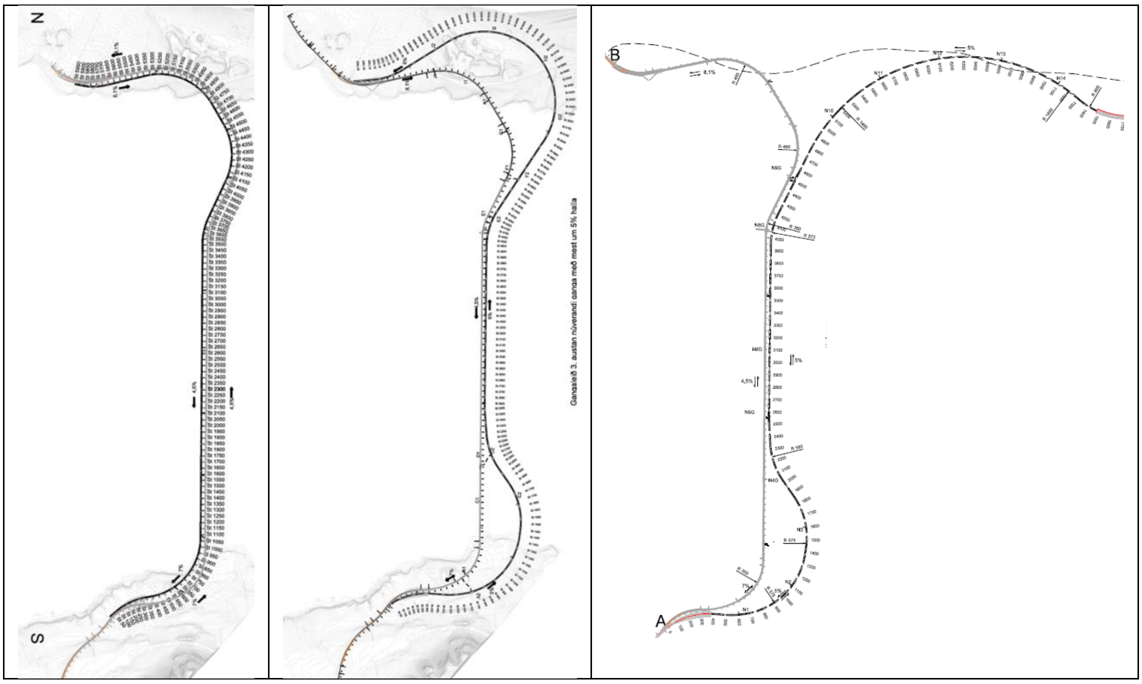
Five alternatives (or routes) have been proposed for extending the existing tunnel, as described in Chapter 4. Because of already performed studies and similarities between the alternatives, only three alternatives are analysed in detail in this report:

Route 2: The new tube has basically the same alignment as the existing tunnel. This alternative is the least costly alternative in terms of construction cost, but the gradient is very high. The new tunnel can either be West or East of the present tunnel. Route 1 is considered a variation of this route. Both tubes are operated with unidirectional traffic.

Route 3. An option with a new tube with wider turns at the slopes for reducing the gradients and at the same time keep the portals at the same place. Route 4 is considered a variation of this route. Both tubes are operated with unidirectional traffic.

Route 5. A new tunnel, where the direction facilitates the largest part of the traffic and provide a shorter driving distance towards Highway No. 1. The present tunnel will be used for traffic towards the community Akranes. Both tunnel tubes are operated in bi-directional traffic mode.

For Alternatives 1- 4, barriers are assumed between lanes with opposite driving direction on the open road on the North-shore of Hvalfjörður. For route 5 barriers shall not be assumed as traffic on that section will be modest.



Route 2 **Route 3** **Route 5**

Figure 1.2 The alignment of three alternative routes: Alternative 2, 3 and 5.

1.2 The objectives of the risk analysis.

The risk analysis covers Hvalfjörður tunnel and the alternatives for extension. In chapter 4, the tunnel is described in more detail. The risk analysis covers the tunnel part and a section of road which is influenced by the various alternatives.

The analysis focuses on the risk to the users of the tunnel, and the objectives of the risk analysis are to document the risk level of the tunnel and evaluate the risk of the alternatives in order to support the decision making for the most feasible extension alternative.

In addition it has been requested to comment on the following statements/questions:

a) Is better to drive up or down on the 8% gradient on the north side?
b) One-directional tunnel has advantages which could be highlighted in the comparison, i.e. overtaking is possible almost without risk, no traffic jam behind heavy vehicles, and in case of fire, smoke can be blown away from tunnel users which is not the case in bi-directional tunnels.
c) For route 5, maintenance and repair can be more easily accomplished as one tunnel can be closed at night time and traffic directed to the other tunnel in meanwhile. For the other alternative routes special measures are needed to change each of the tunnel tubes into bi-directional tunnels with necessary signals and extra costs, probably also increased risk.
d) Emergency rooms without exit to the open is not accepted by the European regulation, but Norwegians aim at getting an approval for this.
e) Would it be better to have a wider tunnel cross section for the first 300 to 500 m such that barrier can be placed between the opposite driving lanes?

2 Risk related basis

2.1 Alternative 2 / Route 2, general information

Geometry	Upgraded present tunnel	New tunnel tube
Length of tunnel	5.770 km	5.770 km
Max slope	8.1%	8.1%
Tunnel cross section	T8.5 (2 lane) and T11 (North with 8.1%)	T9.5
Lane width (m)	3.25 (3.8 km) and 3.5 (on 2 km in 8.1% slope)	3.50
Walkways	Yes , 0.75 m each side 5% sideslope	1.00 m each side
Concrete wall barrier (Føringskant)	No (to be evaluated)	Yes
Minimum horizontal radius	R = 350 m	R = 500 m
Traffic		
Traffic AADT ~2040	1x7500 veh/day (one direction) +	1x7500 veh/day (one direction)
Traffic AADT 2038 (3%; 2%; 5%)	2x6600 veh/day; 2x5400; 2x9300 veh/day	2x6600 veh/day; 2x5400; 2x9300 veh/day
HGV %	8%	8%
Transport of dangerous goods	0.065%	0.065%
Speed limit	70 km/h	70 km/h
Traffic jams	No	No
Bidirectional traffic	No	No
Ventilation		
Ventilation	Longitudinal	Longitudinal
Design fire	50 MW	50 MW
Minimum air speed provided	3.5 m/s	3.5 m/s
Number of fans	32 reversible + 8 added for 3.5 m/s	
Fire ventilation	Yes	Yes
Minimum thrust force	21000 N	
Impeller diameter of fan	1000 mm	100 mm
Nominal thrust per fan	735 N	770 N
Air flow measurement device	In the middle of tunnel	In the middle of the tunnel
NO/CO measurement device	Every 1500 m	Every 1000 m
Smoke detection	No, only CO sensor and dust sensor	No, only CO sensor and dust sensor
Safety and management systems		
Rumble strips	Rumble strips on side lines	Rumble strips on side lines
Drainage system	Yes, gutter c/c 80 m	Yes, gutter c/c 80 m
Luminance	2 cd/m^2 day; 1 cd/m^2 night	2 cd/m^2 day; 1 cd/m^2 night
Emergency exits:	Cross connections c/c 500 m	Cross connections c/c 500 m
Emergency phones	Every 125 m, connects directly to 112	Every 125 m, connects directly to 112
Fire extinguisher	Every 125 m, 2 x 6 kg dry powder ABC rated	Every 125 m, 2 x 6 kg dry powder ABC rated
Emergency lay-bys	Every 500 m	Every 500 m
Turning bays	Every 1500 m designed for large vehicles	Every 2000 m designed for large vehicles
Blinking light and sign at turning bay	Every 1500 m	Every 2000 m
Speed supervision	Yes	Yes
Markings showing distance to portals	Every 1000 m	Every 1000 m
Markings showing speed limit	In the tunnel and outside the tunnel	In the tunnel and outside the tunnel
Speed camera for ticketing	Inside the tunnel	Inside the tunnel
Traffic surveillance	Cameras at portals + in the tunnel (inc. detec.)	Cameras at portals + in the tunnel (inc. detec.)
Automatic incident detection	Yes	Yes
Red lights to indicate tunnel closure	At both portals inbound traffic	At both portals inbound traffic
Physical barrier to stop traffic.	At both portals inbound traffic	At both portals inbound traffic
Road temperature measurement device	2 devices, at both portals	2 devices, at both portals
Air temperature measurement device	Middle of the tunnel	Middle of the tunnel
Humidity measurement device	Middle of the tunnel	Middle of the tunnel
Communications	Tetra and GSM	Tetra and GSM
Radio interruption	Yes	Yes
Control centre	Yes, 24 h	Yes, 24 h
Oil seperator	Outside of tunnel where water is discharged	Outside of tunnel where water is discharged

Table 2.1 Key information about the design and equipment in the Hvalfjörður Tunnel, Alternative 2.

2.2 Alternative 3 / Route 3

Geometry	Upgraded present tunnel	New tunnel tube
Length of tunnel	5.770 km	7.405 km
Max slope	8.1%	5.0%
Tunnel cross section	T8.5 (2 lane) and T11 (North with 8.1%)	T9.5
Lane width (m)	3.25 (3.8 km) and 3.5 (on 2 km in 8.1% slope)	3.5
Walkways	Yes , 0.75 m each side 5% sideslope	1.00 m each side
Concrete wall barrier (Føringskant)	No (to be evaluated)	Yes
Minimum horizontal radius	R = 350 m	R = 500 m
Traffic		
Traffic AADT ~2040	1x7500 veh/day (one direction) +	1x7500 veh/day (one direction)
Traffic AADT 2038 (3%; 2%; 5%)	1x6600 veh/day; 1x5400; 1x9300 veh/day +	1x6600 veh/day; 1x5400; 1x9300 veh/day
HGV %	8%	8%
Transport of dangerous goods	0.065%	0.065%
Speed limit	70 km/h	70 km/h
Traffic jams	No	No
Bidirectional traffic	No	No
Ventilation		
Ventilation	Longitudinal	Longitudinal
Design fire	50 MW	50 MW
Minimum air speed provided	3.5 m/s	3.5 m/s
Number of fans	32 reversible + 8 added for 3.5 m/s	
Fire ventilation	Yes	Yes
Minimum thrust force	21000 N	
Impeller diameter of fan	1000 mm	100 mm
Nominal thrust per fan	735 N	770 N
Air flow measurement device	In the middle of tunnel	In the middle of tunnel
NO/CO measurement device	Every 1500 m	Every 1000 m
Smoke detection	No, only CO sensor and dust sensor	No, only CO sensor and dust sensor
Safety and management systems		
Rumble strips	Rumble strips on side lines	Rumble strips on side lines
Drainage system	Yes, gutter c/c 80 m	Yes, gutter c/c 80 m
Luminance	2 cd/m^2 day; 1 cd/m^2 night	2 cd/m^2 day; 1 cd/m^2 night
Emergency exits:	Cross connection / emergency rooms c/c 500 m	Cross connection / emergency rooms c/c 500 m
Emergency phones	Every 125 m, connects directly to 112	Every 125 m, connects directly to 112
Fire extinguisher	Every 125 m, 2 x 6 kg dry powder ABC rated	Every 125 m, 2 x 6 kg dry powder ABC rated
Emergency lay-bys	Every 500 m	Every 500 m
Turning bays	Every 1500 m designed for large vehicles	Every 2000 m designed for large vehicles
Blinking light and sign at turning bay	Every 1500 m	Every 2000 m
Speed supervision	Yes	Yes
Markings showing distance to portals	Every 1000 m	Every 1000 m
Markings showing speed limit	In the tunnel and outside the tunnel	In the tunnel and outside the tunnel
Speed camera for ticketing	Inside the tunnel	Inside the tunnel
Traffic surveillance	Cameras at portals + in the tunnel (inc. detec.)	Cameras at portals + in the tunnel (inc. detec.)
Automatic incident detection	Yes	Yes
Red lights to indicate tunnel closure	At both portals inbound traffic	At both portals inbound traffic
Physical barrier to stop traffic.	At both portals inbound traffic	At both portals inbound traffic
Road temperature measurement device	2 devices, at both portals	2 devices, at both portals
Air temperature measurement device	3 devices, at both portals and close to middle	3 devices, at both portals and close to middle
Humidity measurement device	3 devices, at both portals and close to middle	3 devices, at both portals and close to middle
Communications	Tetra and GSM	Tetra and GSM
Radio interruption	Yes	Yes
Control centre	Yes, 24 h	Yes, 24 h
Oil seperator	Outside of tunnel where water is discharged	Outside of tunnel where water is discharged

Table 2.2 Key information about the design and equipment in the Hvalfjörður Tunnel, Alternative 3.

2.3 Alternative 5 / Route 5

Geometry	Upgraded present tunnel	New tunnel tube
Length of tunnel	5.770 km	7.540 km
Max slope	8.1%	5.0%
Tunnel cross section	T8.5 (2 lane) and T11 (North with 8.1%)	T10.5
Lane width (m)	3.25 (3.8 km) and 3.5 (on 2 km in 8.1% slope)	3.50 m
Walkways	Yes , 0.75 m each side 5% sideslope	1.00 m each side + 1.00 m between lanes
Concrete wall barrier (Føringskant)	No (to be evaluated)	Yes
Minimum horizontal radius	R = 350 m	R = 500 m
Traffic		
Traffic AADT ~2040	35% of total traffic	65% of total traffic
Traffic AADT ~2040	2x2625 veh/day (two directions) +	2x4875 veh/day (two directions)
Traffic AADT 2038 (3%; 2%; 5%)	2x4600 veh/day; 2x3800; 2x6500 veh/day +	2x8600 veh/day; 2x7000; 2x12100 veh/day
HGV %	8%	8%
Transport of dangerous goods	0.065%	0.065%
Speed limit	70 km/h	70 km/h
Traffic jams	No	No
Bidirectional traffic	No	No
Ventilation		
Ventilation	Longitudinal	Longitudinal
Design fire	50 MW	100 MW
Minimum air speed provided	3.5 m/s	4.5 m/s
Number of fans	32 reversible + 8 added for 3.5 m/s	
Fire ventilation	Yes	Yes
Minimum thrust force	21000 N	
Impeller diameter of fan	1000 mm	1000 mm
Nominal thrust per fan	735 N	770 N
Air flow measurement device	In the middle of tunnel	In the middle of tunnel
NO/CO measurement device	Every 1500 m	Every 1000 m
Smoke detection	No, only CO sensor and dust sensor	No, only CO sensor and dust sensor
Safety and management systems		
Rumble strips	Rumble strips on side lines	Two rumble strips at center and on side lines
Drainage system	Yes, gutter c/c 80 m	Yes, gutter c/c 80 m
Luminance	2 cd/m^2 day; 1 cd/m^2 night	2 cd/m^2 day; 1 cd/m^2 night
Emergency exits:	Cross connection / emergency rooms c/c 500 m	Cross connection / emergency rooms c/c 500 m
Emergency phones	Every 125 m, connects directly to 112	Every 125 m, connects directly to 112
Fire extinguisher	Every 125 m, 2 x 6 kg dry powder ABC rated	Every 125 m, 2 x 6 kg dry powder ABC rated
Emergency lay-bys	Every 500 m	Every 250 m
Turning bays	Every 1500 m designed for large vehicles	Every 1000 m designed for large vehicles
Blinking light and sign at turning bay	Every 1500 m	Every 1000 m
Speed supervision	Yes	Yes
Markings showing distance to portals	Every 1000 m	Every 1000 m
Markings showing speed limit	In the tunnel and outside the tunnel	In the tunnel and outside the tunnel
Speed camera for ticketing	Inside the tunnel	Inside the tunnel
Traffic surveillance	Cameras at portals + in the tunnel (inc. detec.)	Cameras at portals + in the tunnel (inc. detec.)
Automatic incident detection	Yes	Yes
Red lights to indicate tunnel closure	At both portals inbound traffic	At both portals inbound traffic
Physical barrier to stop traffic.	At both portals inbound traffic	At both portals inbound traffic
Road temperature measurement device	2 devices, at both portals	2 devices, at both portals
Air temperature measurement device	3 devices, at both portals and close to middle	3 devices, at both portals and close to middle
Humidity measurement device	3 devices, at both portals and close to middle	3 devices, at both portals and close to middle
Communications	Tetra and GSM	Tetra and GSM
Radio interruption	Yes	Yes
Control centre	Yes, 24 h	Yes, 24 h
Oil seperator	Outside of tunnel where water is discharged	Outside of tunnel where water is discharged

Table 2.3 Key information about the design and equipment in the Hvalfjörður Tunnel, Alternative 5.

2.4 Traffic

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

- Traffic volume per tube (including its distribution during day, week, year),

- Presence and percentage of heavy goods vehicles,
- Risk of congestion (daily or seasonal),
- Speed limits for the traffic and its enforcement

Traffic prognosis

The traffic prognosis is discussed in appendix chapter 9: For the year 2019 and ~2040 the traffic is expected as shown in Table 2.4. The traffic is close to be the same in both directions. For Alternative 5, the traffic distributes with 35% in the existing tunnel tube and 65% in the new tunnel tube.

Hvalfjörður Tunnel		[veh/d]				
	Pct.	2019	2038 low	2038 best	2038 high	**~2040**
AADT (PV + other) tunnel	92%	7222	9936	12144	17112	**13800**
AADT (HGV) tunnel	8%	628	864	1056	1488	**1200**
AADT (total) tunnel	100%	7850	10800	13200	18600	**15000**

Table 2.4 Traffic prognosis for Hvalfjörður Tunnel

The daily distribution of traffic is described in detail in the document Hvalfjarðargöng, Umferðarúttekt – Umferðarspá [3]. Figure 2.1 below illustrate the distribution over the day, for the year 2004 (where AADT was 4103 veh/day). The traffic has a peak in the afternoon and is increased on Fridays and Sundays.

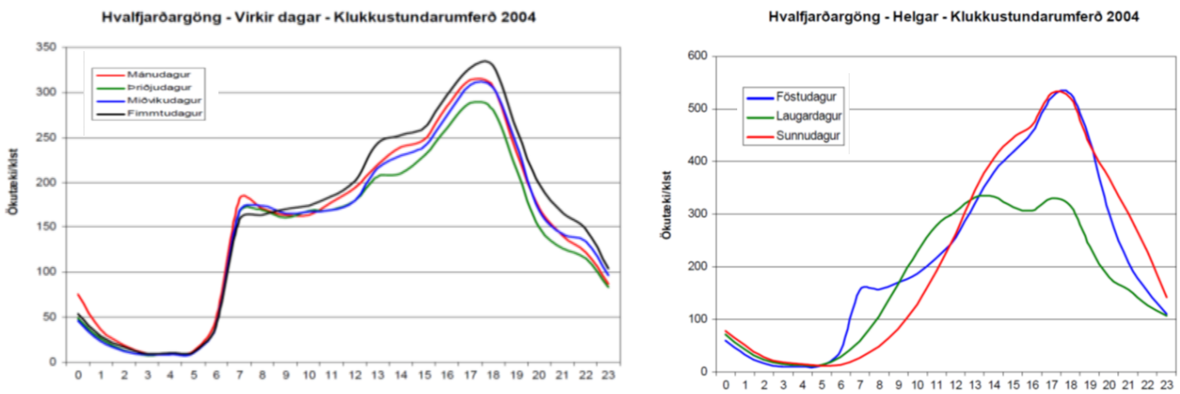


Figure 2.1 Traffic distribution over day. Left: Monday-Thursday, right Friday – Sunday.

Based on the above mentioned traffic prognosis, the hourly traffic is forecasted for ~2040 as illustrated in Figure 2.2. Peak traffic occurs at weekends and in the summertime. week and year

<u>Hourly traffic ~2040 (using main traffic assumption)</u>

<u>For Alternatives 1-4:</u>

- afternoon peak: approximately 650 veh/h (average day)
- The peak hour traffic in weekends in the summer time (Fri/Sun; July) will presumably be approximately 1300 veh/h in ~2040.

<u>For Alternative 5, existing tunnel tube:</u>

- afternoon peak: approximately 450 veh/h (average day)

<u>For Alternative 5, new tunnel tube:</u>

- afternoon peak: approximately 850 veh/h (average day)
- The peak hour traffic in weekends in the summer time (Fri/Sun; July) will presumably be approximately 1700 veh/h in ~2040.

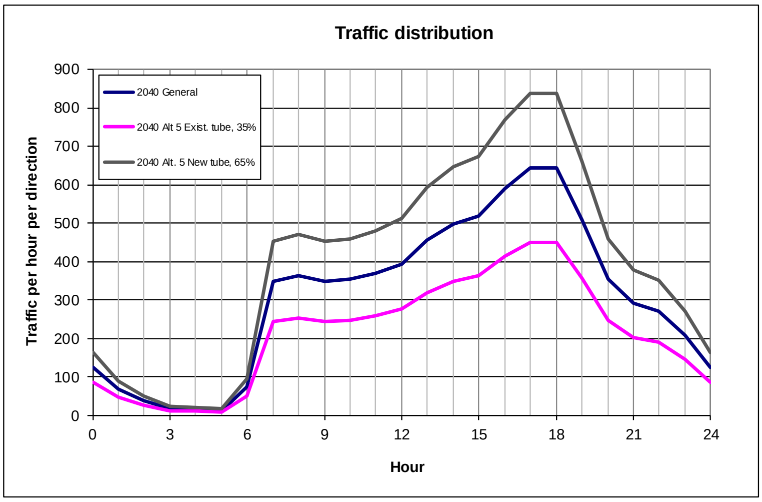


Figure 2.2 *Assumed daily distribution of the traffic forecasted for ~2040 based on the registration of 2004 and using the main traffic assumption (AADT = 15000 veh/day).*

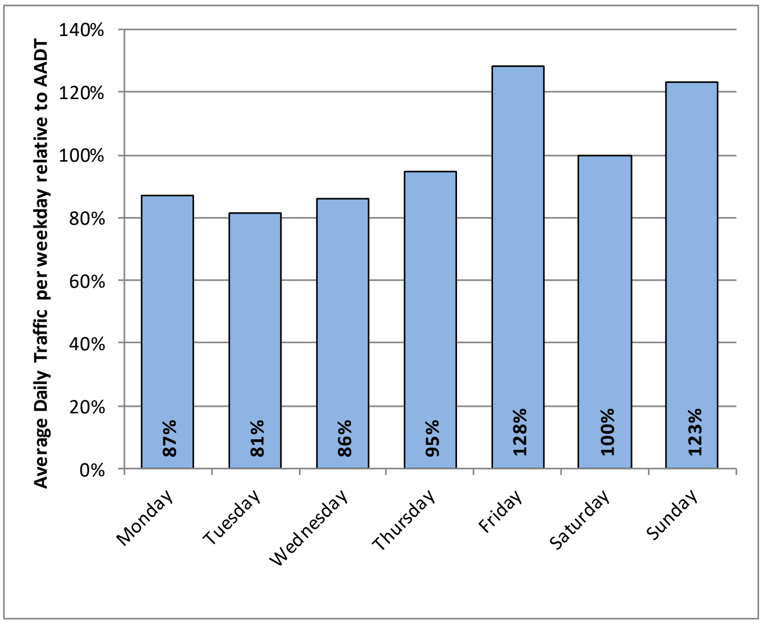


Figure 2.3 *Traffic distribution over the week: weekday average traffic and its percentage of AADT (2004 figures)*

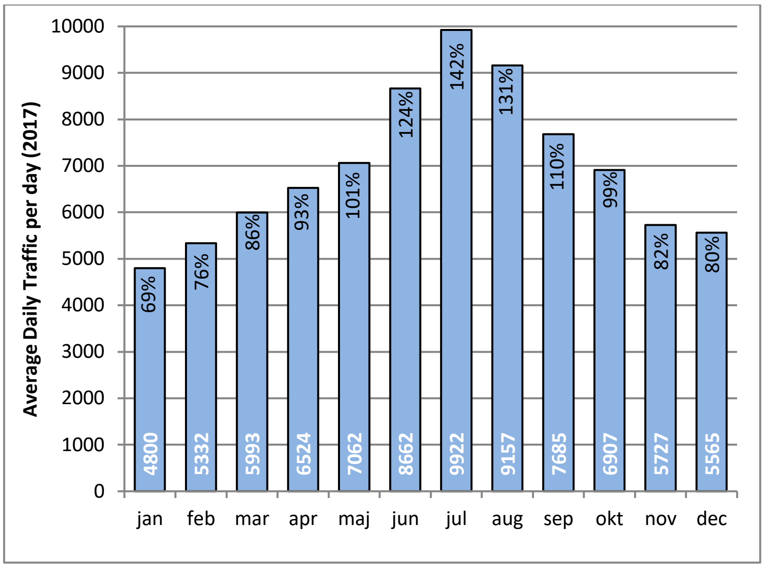


Figure 2.4 Traffic distribution over the year: monthly average daily traffic and its percentage of AADT (2017 figures)

Portion of heavy traffic

The assumption of portion of heavy traffic has been provided by Vegagerðin based on Information from the road toll collection. The percentage of heavy goods vehicles (HGVs) is set to 8.0% out of the AADT of 15000 veh/day. The traffic with (large) buses are included in the portion, and is assumed to be approximately 2.0% of AADT. These figures are used in the present risk analysis.

Dangerous goods

Traffic with dangerous goods is presently restricted in peak hours, Table 2.5:

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

Table 2.5 Peak hours where dangerous goods is restricted

The transport of dangerous goods has been provided by Vegagerðin based on information from the road toll collection. The transport of dangerous goods transports is estimated to 0.065% of the AADT, corresponding to ~0.8% of the HGV traffic. In absolute numbers this is in average ~5 vehicles per day in 2019 and ~10 vehicles per day in ~2040 based on the main assumption.

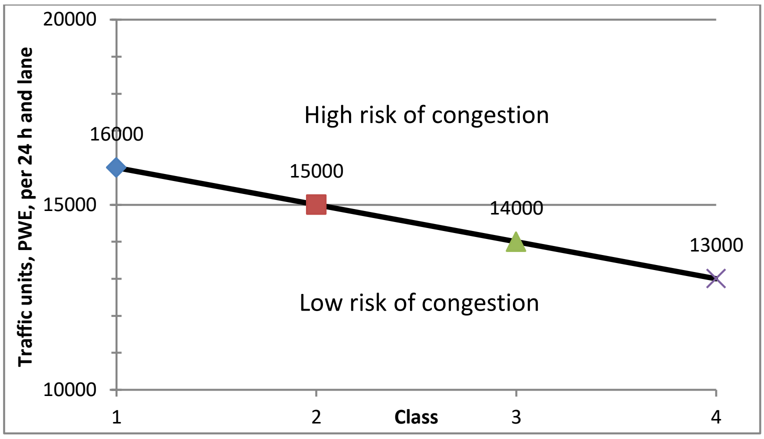
Capacity / Traffic congestion

At present there is no problems of congestion in the Hvalfjörður tunnel. The risk of congestion can be evaluated based on guidelines (for example ASTRA 13001). The AADT expected for 2019 of 7850 veh/day is assumed distributed approximately 50%/50% in the two directions, and the HGV share is 8% including buses. The daily traffic in the summer months is 9800 veh/day. On this basis the vehicle units per 24 hours and lane (see Figure 2.5) can be determined to presently 4300 PWE/lane and 5300 PWE/lane in the summer months. On specific days possibly 6500 PWE/lane.

With the reference AADT of 15000 the traffic would correspond to 8100 PWE/lane for 2 lanes and with the extension to 4 lanes it would be

4050 PWE/lane. On specific summer days possibly 13000 PWE/lane for 2 lanes, and 6000 PWE/lane for the extended tunnel system with 4 lanes.

Figure 2.5 illustrates that in case of Class 3: tunnels with holiday traffic the limit of the high risk of congestion is met at 14000 PWE and for traffic from tourist centres at 13000 PWE.



Classes are related to the prevailing purpose of the traffic.

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). At merging lanes in or near the tunnel limits are reduced 20%.

Figure 2.5 *Frequency of congestion (corresponding to Figure II.2 in ASTRA 13001) in tunnels with unidirectional traffic characterised as high or low frequency of congestion.*

It appears that there is no high risk of congestion in the tunnel presently at normal operation. If the tunnel is extended to four lanes, the risk of congestion is also low at the end of the considered time span. If the tunnel system is not expanded to four lanes, the risk of congestion may be increased at the end of the considered time span.

Speed limits

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

2.5 Accident frequencies for Iceland

2.5.1 All roads

The fatality rate for all road traffic in Iceland in the year 2018 shown in Table 2.6 are in accordance with the low end of the West-European frequencies.

Fatal Accidents 2018		
All roads	18	fatalities
All roads	$4.8\ 10^{-9}$	fatalities per veh-km

Table 2.6 Frequencies fatalities in Iceland for 2018.

Frequency of fatalities on all roads is 4.8 fatalities per billion veh-km (2018 – statistics), which is a low figure compared with other European countries. However, the Icelandic statistics appears to be more volatile than other statistics (presumably because of the relatively few number of accidents) – and in the previous 10 year the fatality rate in 2009 was 8.0 fatalities per billion veh-km and in 2014 it was a record low 1.2 fatalities per billion veh-km. If the development is drawn up for the years 1980 – 2018 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 curves might describe the development well. The trend curves 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. The fatality rates in Iceland tend to follow the middle curve, however, since 2010 they have been below the middle trend curve. In the years 2010, 2012 and 2014 the fatality rates have also been below the lower curve, whereas they have been above the lower curve in the years 2013, 2015, 2016, 2017 and 2018.

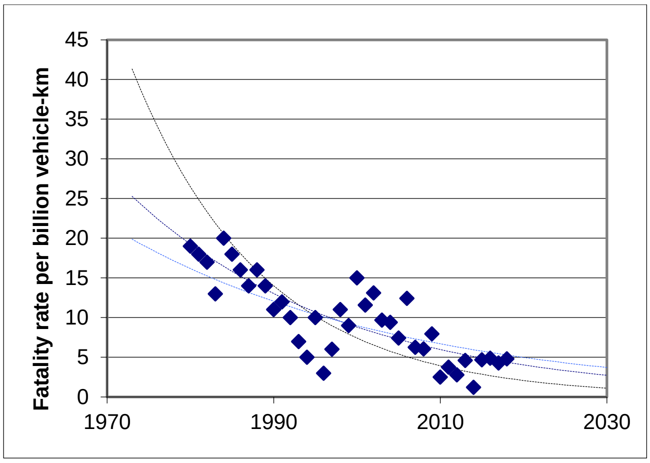


Figure 2.6 Fatality rates in Iceland 1980 to 2018 and trend curves based on Norwegian data.

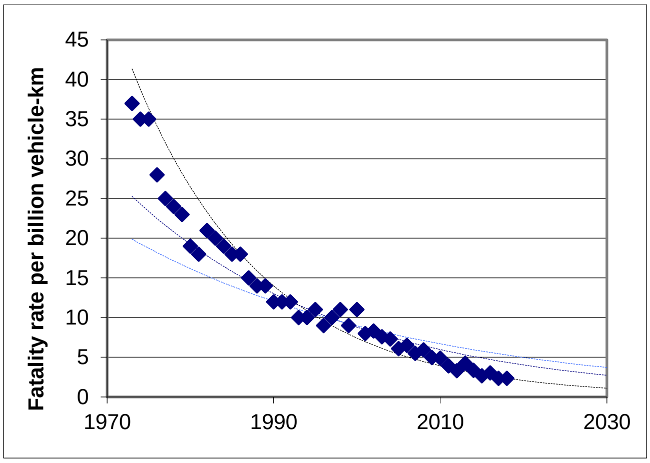


Figure 2.7 Fatality rates in Norway 1970 to 2018 and trend curves.

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

As it appears from data in Figure 2.6 and Figure 2.7 as well as the trend lines, the fatality rates are far from constant with time. The accident frequencies since the late 1970'ies (and actually also in the period before 1970) have followed closely a decreasing exponential trend line.

The same tendency can be observed with respect to the number of accidents and injuries per year and accidents per vehicle km.

The continuation of a corresponding trend line would mean a reduction of the frequency of injury accident per vehicle km in the year ~2040 to between ¼ and ½ of the frequencies of 2018. Using the frequencies of today as basis for the risk analysis will obviously derive an upper value of the future risk.

2.5.2 Rural roads

For the present analysis, the statistics of accidents on rural roads are considered. The data in Table 2.7 and Table 2.8 for the years 2010 – 2016 have been provided by Vegagerðin.

Year	Accidents with				All accidents with damage	Accidents with personal damage
	Material damage	Slight injuries	Serious injuries	Fatalities		
2010	1692	395	79	4	2170	478
2011	1825	409	79	8	2321	496
2012	1647	359	61	6	2073	426
2013	1692	384	81	13	2170	478
2014	1787	357	79	3	2226	439
2015	2066	427	80	12	2585	519
2016	2165	456	92	15	2728	563
Total	**12874**	**2787**	**551**	**61**	**16273**	**3399**

Table 2.7 Accident on rural roads in Iceland 2010 - 2016.

Year	Length [km]	Traffic [bill. Veh-km]	Accident rate [per mill. veh-km]		Fatality rate [per billion veh-km]
			All accidents	Injury accidents	
2010	9757	1.988	1.0913	0.2404	2.01
2011	9808	1.916	1.2116	0.2589	4.18
2012	9854	1.938	1.0697	0.2198	3.10
2013	9892	1.994	1.0885	0.2398	6.52
2014	10248	2.103	1.0584	0.2087	1.43
2015	10271	2.255	1.1464	0.2302	5.32
2016	10267	2.603	1.0479	0.2163	5.76
Total	**-**	**14.797**	**1.0998**	**0.2297**	**4.12**

Table 2.8 Traffic, accident rates and fatality rates on rural roads in Iceland 2010 - 2016.

In Figure 2.8 the fatality rate on rural roads is compared with the fatality rate on all roads. The fatality rate is generally higher on rural roads than for all roads. In average for the seven years it is 4.12 fatalities per billion veh-km, 18% higher than the corresponding 3.52 fatalities per billion veh-km for all roads. The accident rate for injury accidents is 0.230 accidents per million veh-km in average for the seven years.

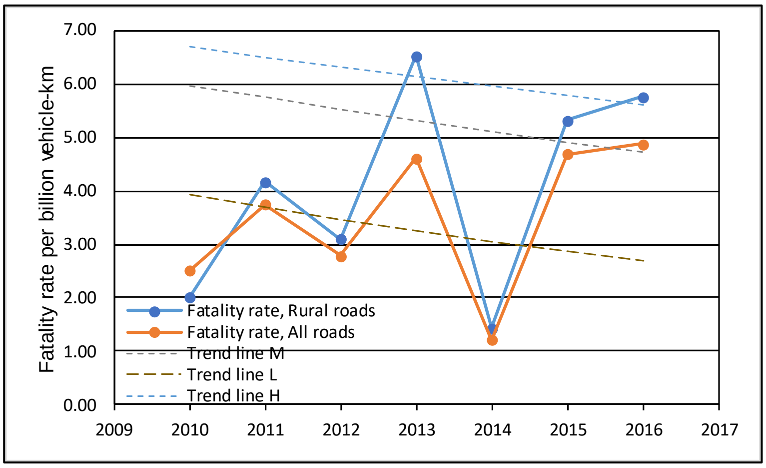


Figure 2.8 Fatality rates for rural roads and all roads in Iceland 2010 to 2016 and trend lines.

3 Risk policy and risk acceptance

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 are shown in Figure 3.1, which illustrate the upper limit, G_{II}, which under no circumstances may be exceeded, and the lower limit, G_I, defining the broadly acceptable risk, at which no considerations have to be made. For risks between these limits, cost-efficiency evaluations of additional safety measure shall be made, and the risk is only characterised as tolerable, when it is proved that all cost-efficient safety measures have been introduced.

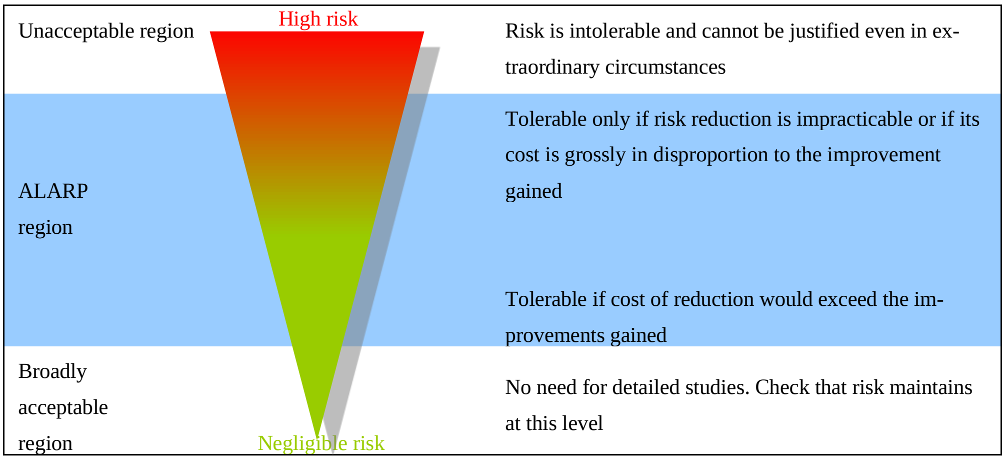


Figure 3.1 ALARP region and acceptance limits.

The upper limit, G_{II}, is specified to that the probability of fatalities in road traffic for each member of the population is less than 10^{-4} [23]. For Iceland, using the data for the years between 1990 and 2018 result in upper limits between 9 and 10 fatalities per billion veh.-km. For the use in the future the lower value of 9.00 fatalities per billion veh.-km is used.

The lower limit, G_I, is defined to $G_{II}/100$, i.e. 0.09 fatalities per billion veh.-km. However, this value is of limited importance.

Average fatality risk on roads in Iceland 2018	4.8	fatalities per billion veh km
Upper limit, G_{II}	9.0	fatalities per billion veh km
Lower limit, G_I	0.09	fatalities per billion veh km

Table 3.1 Limits for the tunnel risk in Iceland.

Marginal costs

In the ALARP zone below the upper limit, G_{II}, the risk is tolerable when all relevant risk reducing measures have been evaluated and introduced unless their cost is (grossly) in disproportion to the improvements gained. This is proven by the use of marginal costs of substitution [23]. By use of this principle the relevant improvements (safety measures) are evaluated with respect to their marginal effect on the risk and the cost of these measures.

The marginal costs will generally be measured in monetary units. If the safety measure has other disadvantages, they should be transformed into monetary units. The marginal costs should for comparison be formulated as annual costs. Annuity functions with annuity factor, γ, and a cost factor, λ, can be used for the transformation.

	Annual rate
Annuity rate, γ	5%
Inflation rate λ	1%

Table 3.2 Assumed annuity rate and inflation rate

The safety measures result in improvements of the risk, which is measures in (less) fatalities, injuries and material costs. Hence, various types of consequences must be associated the with "marginal costs" or weight factors, which can facilitate comparison. For the present study the weight factors (the benefit of the society of avoiding road accidents) have been based on an estimate using the values which are common practice in Norway [24] and Finland as shown in Table 3.3.

	2016 EUR
Fatalities	3'000'000
Very severe injuries	2'700'000
Severe injuries	950'000
Light injuries	72'000
Material damage	4'000

Notes: The difference between 2016-values and 2020 values is considered marginal.
Conversion rate 10.18 NOK/EUR.
Material damage is for average road traffic accidents.
Material damage for accidents in tunnels may be higher

Table 3.3 Marginal costs / weight factors for personal damages, i.e. the benefit of the society of avoiding road accident. Rounded 2016 values from [24] converted to EUR.

Large accidents and risk aversion

Large accidents with many fatalities are sometimes 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. There are several ways to give priority to large accidents. As a supplement (replacing risk aversion) it can be taken into account that large accident may have secondary effects. The consequences of these secondary effects can be modelled and be integrated in the aggregated consequences.

In the present risk analysis, the risk aversion is not treated specifically.

Disruption of traffic / Traffic disturbance

Disruption of traffic and traffic disturbance can be a major consequence of events in the tunnel. In the present study the traffic disturbance is included as cost for driving 123 ISK/km, (this cost assumes that 10% of the traffic is heavy vehicles) data given in [11]. This corresponds to 0.90 EUR/km. The figure is based on QRUS-model software owned by the Icelandic Road Authority (IRA), which also state an interest rate of 5% and average estimated. The values are higher than those given in [32], and it is assumed that also time-dependent costs are included.

4 Definition of the tunnel system

4.1 Geometry of the existing tunnel tube

The geometry of the existing tunnel is described below. The risk of the existing tunnel has been determined for comparison as documented in Appendix chapter 10, and the existing tube is part of the extended tunnel system in Alternatives 2, 3 and 5.

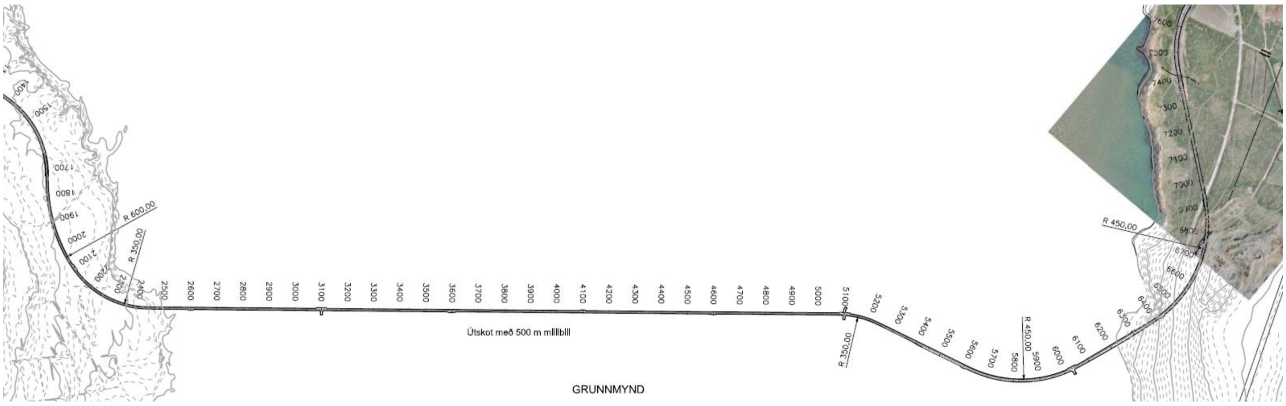


Figure 4.1 *Alignment of the existing Hvalfjörður tunnel (North to the right)*

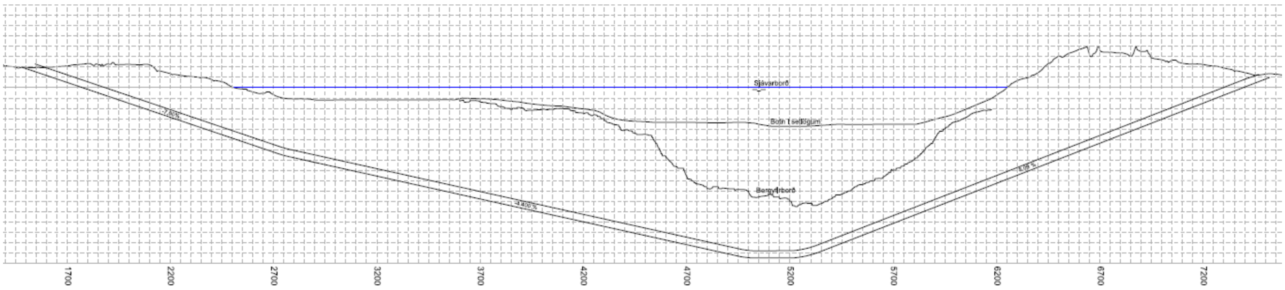


Figure 4.2 *Longitudinal profile for Hvalfjörður tunnel (North to the right)*

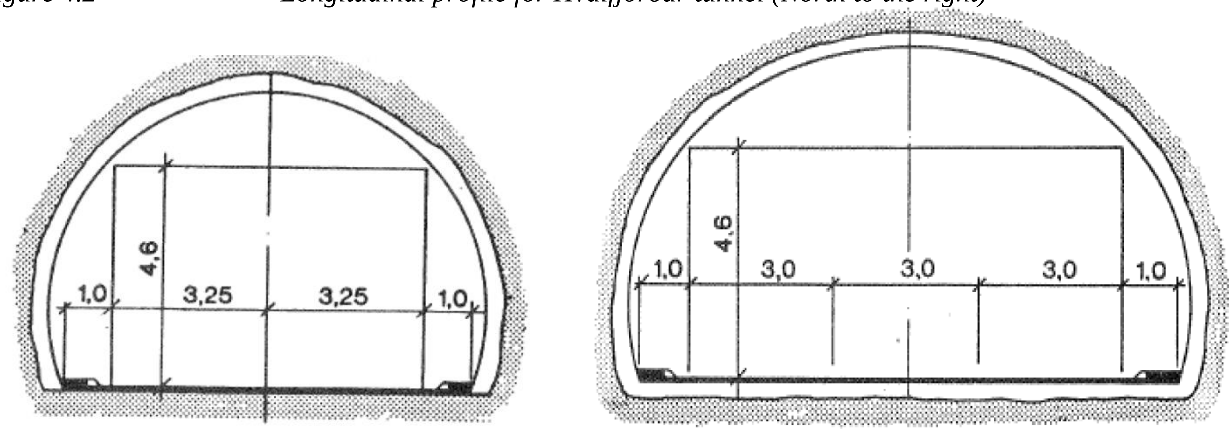


Figure 4.3 *Principal lay-out of cross section of tunnel (unit: m).*

4.2 New tunnel tube: Alternative 2

The geometry of Alternative 2 is described below. The existing tunnel tube will be used for unidirectionally northbound traffic. The geometry of the tube is generally described in Appendix chapter 10 with the following exceptions:

- Unidirectional traffic: 50% of AADT
- 2 lanes in the entire tunnel, lane width 3.50 m in a 2 km section (T11, 8.1%)
- Concrete wall barrier (Føringskant) to be considered
- Cross passages every 500 m.
- Rumble strips on both side lines

Alignment, New tunnel tube (Alternative 2)

The new tube has basically the same alignment as the existing tunnel as shown in Figure 4.1 and Figure 4.2. The geometry of the tunnel tube has been modelled in 18 sections as described in Table 4.1.

South bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT veh/day
H1s		5950	50	500	-4.33	2	3.50	7500
H2s	N Portal	5900	50	500	-4.33	2	3.50	7500
H3s		5850	100	500	-4.33	2	3.50	7500
H4s		5750	350	∞	-8.09	2	3.50	7500
H5s		5400	650	500	-8.09	2	3.50	7500
H6s		4750	200	∞	-8.09	2	3.50	7500
H7s		4550	450	500	-8.09	2	3.50	7500
H8s		4100	375	∞	-8.09	2	3.50	7500
H9s		3725	35	500	-8.09	2	3.50	7500
H10s		3690	210	500	0	2	3.50	7500
H11s		3480	879	∞	4.43	2	3.50	7500
H12s		2601	1291	∞	4.43	2	3.50	7500
H13s		1310	250	∞	7	2	3.50	7500
H14s		1060	630	500	7	2	3.50	7500
H15s		430	150	∞	7	2	3.50	7500
H16s		280	100	500	7	2	3.50	7500
H17s		180	50	500	5.26	2	3.50	7500
H18s	S Portal	130	50	500	5.26	2	3.50	7500

Table 4.1 Alt. 2: Tunnel tube geometry and traffic. The tunnel is divided into 18 sections. Traffic AADT is given for the year ~2040 and covers the southbound direction.

Cross sections

The tunnel cross section of the new tunnel tube is T9.5, and the lane width is 3.50 m corresponding to current practice. The tunnel tube has a concrete wall barrier (Føringskant) and walkways are located on each side with 1.00 m width.

Emergency exits and lay-bys

The new tunnel tube has emergency exits through cross passages to the existing tunnel tube with a distance of 500 m. The exits are located at the lay-bys (every 500 m). Turning bays designed for large vehicles are located for every 2000 m.

4.3 New tunnel tube: Alternative 3

The geometry of Alternative 3 is described below. The existing tunnel tube will be used for unidirectionally southbound traffic. The geometry of the tube is generally described in section 4.1 with the following exceptions:

- Unidirectional traffic: 50% of AADT
- 2 lanes in the entire tunnel, lane width 3.50 m in a 2 km section (T11, 8.1%)
- Concrete wall barrier (Føringskant) to be considered
- Cross passages or emergency rooms are located for every 500 m.
- Rumble strips on both side lines

Alignment, New tunnel tube (Alternative 3)

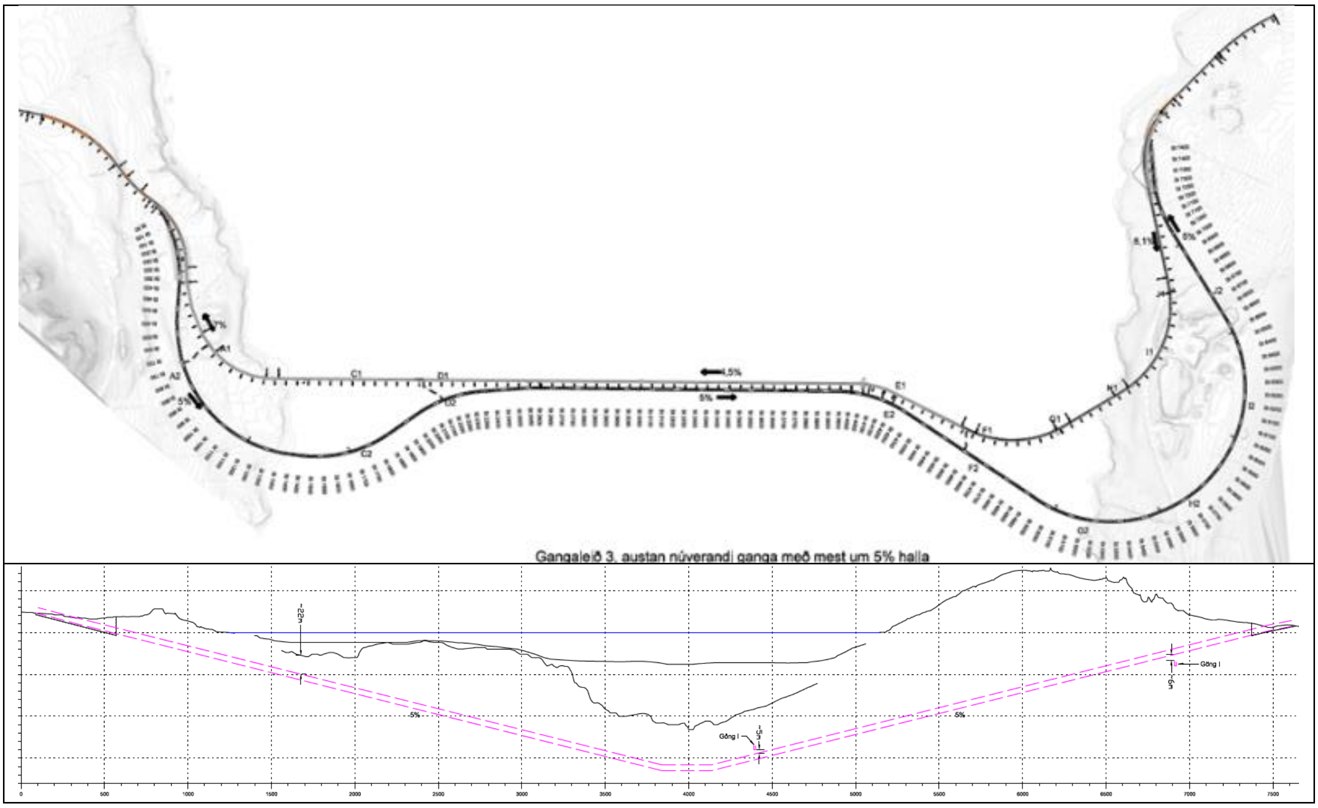


Figure 4.4 The alignment of Alternative 3 (North to the right)

North bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
H1n		65	50	500	-4.95	2	3.50	7500
H2n	S Portal	115	50	500	-4.95	2	3.50	7500
H3n		165	50	500	-4.95	2	3.50	7500
H4n		215	50	500	-5.01	2	3.50	7500
H5n		265	135	∞	-5.01	2	3.50	7500
H6n		400	100	∞	-5.01	2	3.50	7500
H7n		500	1295	575	-5.01	2	3.50	7500
H8n		1795	155	∞	-4.44	2	3.50	7500
H9n		1950	450	585	-4.44	2	3.50	7500
H10n		2400	1450	∞	-4.44	2	3.50	7500
H11n		3850	240	575	0	2	3.50	7500
H12n		4090	160	575	4.99	2	3.50	7500
H13n		4250	700	∞	4.99	2	3.50	7500
H14n		4950	1700	600	4.99	2	3.50	7500
H15n		6650	350	∞	4.99	2	3.50	7500
H16n		7000	330	585	4.99	2	3.50	7500
H17n		7330	40	585	4.98	2	3.50	7500
H18n		7370	100	585	4.98	2	3.50	7500
H19n		7470	50	585	4.98	2	3.50	7500
H20n	N Portal	7520	50	585	4.98	2	3.50	7500

Table 4.2 Alt. 3: Tunnel tube geometry and traffic. The tunnel is divided into 18 sections. Traffic AADT is given for the year ~2040 and covers the southbound direction.

The new tube has a longer alignment compared to the existing tunnel tube as shown in Figure 4.4. The wider turns on the upward and downwards slopes reduce the gradient with remained positions of the portals. On the other hand the total length of the tunnel tube is 7405 m, i.e. 1635 m longer than the existing tunnel tube. The geometry of the tunnel tube has been modelled in 20 sections.

Cross sections
The tunnel cross section of the new tunnel tube is T9.5, and the lane width is 3.50 m corresponding to current practice. The tunnel wall is lined with a concrete wall barrier, and walkways are located on each side with 1.00 m width.

Emergency exits and lay-bys
The new tunnel tube has emergency exits through cross passages to the existing tunnel tube with a distance of 500 m. At locations, where cross passages are impossible, emergency exits are connected to emergency rooms, designed as a safe haven during a fire. The exits are located at the lay-bys (every 500 m). Turning bays designed for large vehicles are located for every 2000 m.

4.4 New tunnel tube: Alternative 5

The geometry of Alternative 5 is described below. In Alternative 5 the new tunnel tube and the existing tunnel tube will be independent bidirectional tunnels with the North portal located at different locations. The geometry of the existing tunnel tube is generally described in section 4.1 with the following exceptions:

- Bi-directional traffic: 35% of total AADT
- Cross passages or emergency rooms are located for every 500 m.
- Rumble strips on both side lines

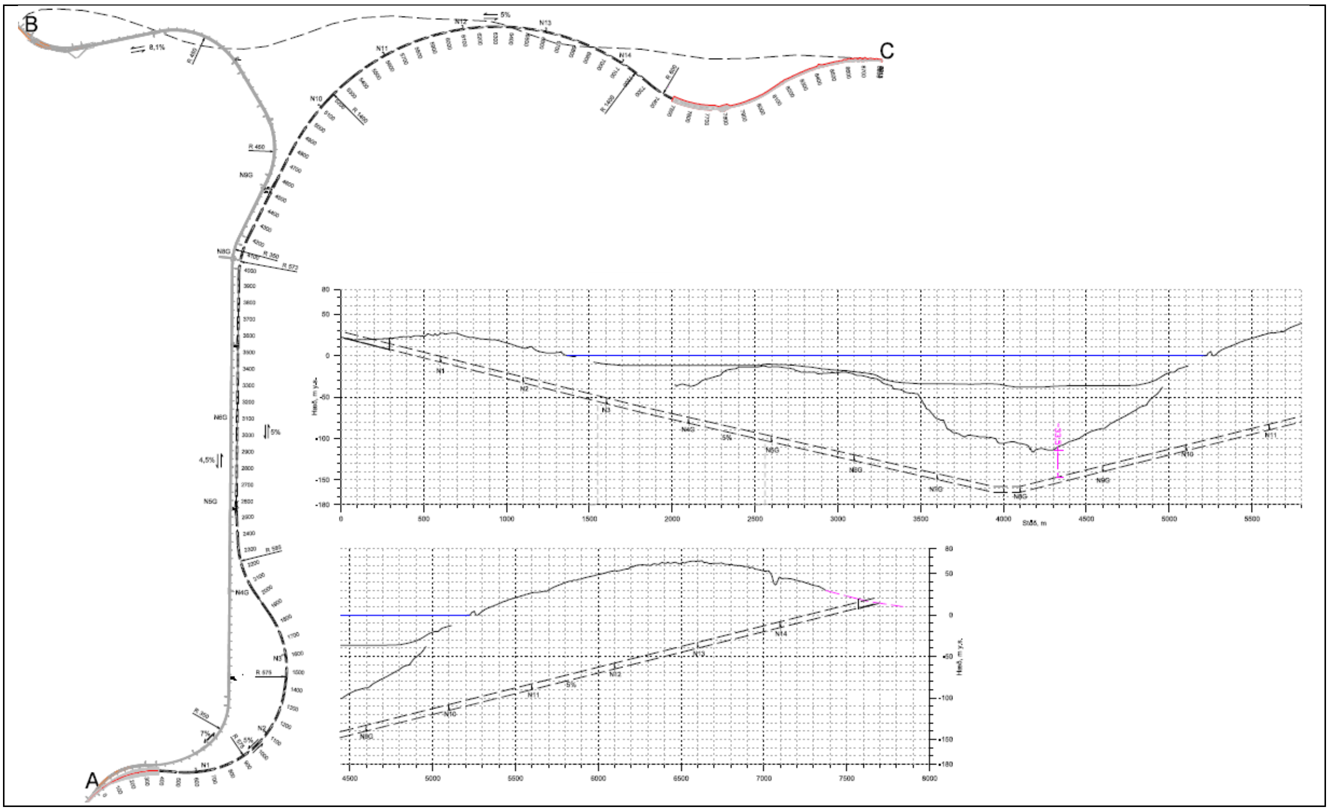


Figure 4.5 The alignment of Alternative 5 (North upwards)

Alignment, New tunnel tube (Alternative 5)

The location of the Southern portal is the same as for the existing tunnel, whereas the Northern portal of the new tunnel is located roughly 3 km East of the existing Northern portal. The new tube has a longer alignment compared to the existing tunnel tube as shown in Figure 4.5. The total length of the tunnel tube is 7540 m, i.e. 1770 m longer than the existing tunnel tube. The wider turns at the Southern slope and the longer tunnel arm towards Northeast reduce the gradients. The geometry of the tunnel tubes is modelled in 2x20 sections.

North bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
H1n		165	50	500	-4.95	1	3.50+	4875
H2n	S Portal	215	50	500	-4.95	1	3.50+	4875
H3n		265	100	500	-4.98	1	3.50+	4875
H4n		365	100	500	-4.98	1	3.50+	4875
H5n		400	35	∞	-4.98	1	3.50+	4875
H6n		500	1340	575	-4.98	1	3.50+	4875
H7n		1840	210	∞	-4.98	1	3.50+	4875
H8n		2050	300	585	-4.44	1	3.50+	4875
H9n		2350	250	2000	-4.44	1	3.50+	4875
H10n		2600	1295	∞	-4.44	1	3.50+	4875
H11n		3895	55	∞	0	1	3.50+	4875
H12n		3950	200	573	0	1	3.50+	4875
H13n		4150	200	573	5.00	1	3.50+	4875
H14n		4350	450	∞	5.00	1	3.50+	4875
H15n		4800	1500	1400	5.00	1	3.50+	4875
H16n		6300	1083	1400	5.00	1	3.50+	4875
H17n		7383	172	600	4.99	1	3.50+	4875
H18n		7555	100	600	4.99	1	3.50+	4875
H19n		7655	50	600	4.99	1	3.50+	4875
H20n	N Portal	7755	50	600	4.99	1	3.50+	4875

South bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT veh/day
H1s		7805	50	600	-4.99	1	3.50+	4875
H2s	N Portal	7755	50	600	-4.99	1	3.50+	4875
H3s		7655	100	600	-4.99	1	3.50+	4875
H4s		7555	172	600	-4.99	1	3.50+	4875
H5s		7383	1083	1400	-5.00	1	3.50+	4875
H6s		6300	1500	1400	-5.00	1	3.50+	4875
H7s		4800	450	∞	-5.00	1	3.50+	4875
H8s		4350	200	573	-5.00	1	3.50+	4875
H9s		4150	200	573	0.00	1	3.50+	4875
H10s		3950	55	∞	0.00	1	3.50+	4875
H11s		3895	1295	∞	4.44	1	3.50+	4875
H12s		2600	250	2000	4.44	1	3.50+	4875
H13s		2350	300	585	4.44	1	3.50+	4875
H14s		2050	210	∞	4.98	1	3.50+	4875
H15s		1840	1340	575	4.98	1	3.50+	4875
H16s		500	100	∞	4.98	1	3.50+	4875
H17s		400	35	500	4.98	1	3.50+	4875
H18s		365	100	500	4.98	1	3.50+	4875
H19s		265	50	500	4.95	1	3.50+	4875
H20s	S Portal	215	50	500	4.95	1	3.50+	4875

Table 4.3 Alt. 5: Tunnel tube geometry and traffic. The tunnel is divided into 18 sections. Traffic AADT is given for the year ~2040 and covers the southbound direction. $^{+}$The lane width is 3.50 m, in addition a 1 m wide central reserve is available.

Cross sections

The new tunnel tube is designed with a T10.5 cross section; the two lanes are 3.50 m wide and are divided with a 1.00 m wide central reserve. The tunnel wall is lined with a concrete barrier and 1.00 m wide walkways on each side.

Emergency exits and lay-bys

The new tunnel tube has emergency exits through cross passages to the existing tunnel tube with a distance of 500 m. At locations, where cross passages are impossible, emergency exits are connected to emergency rooms, designed as a safe haven during a fire. The exits are located at every second lay-by (every 500 m). Lay-bys are located every 250 m. Turning bays designed for large vehicles are located for every 1000 m.

4.5 Ventilation

New tunnel tube: Alternative 2 and 3

In the existing tube the ventilation is improved with eight additional fans, which makes it possible to control a 50 MW fire and obtain an air speed of 3.5 m/s. The new tunnel tube will be equipped with a similar ventilation system.

New tunnel tube: Alternative 5

In the existing tunnel tube the presently available ventilation will be maintained. The new tunnel tube will be equipped with a ventilation system which makes it possible to control a 100 MW fire and obtain an air speed of 4.5 m/s

4.6 Tunnel lighting

New tunnel tubes and the upgraded existing tunnel tube

The lighting is designed to the same standard as the existing tunnel tube. The luminance is 2 cd/m^2 at daytime and 1 cd/m^2 at night.

LED lights will be installed on curb stone with 25 m interval for existing tube as well as the new tubes.

4.7 Construction costs

The construction costs for the refurbishment of the existing tunnel tube and the construction of the new tunnel tube are listed and described in [11] and summarised in Table 4.4 below.

	Construction costs, new tube	Cost of refurbishment of existing tunnel	Total project costs	Total project costs
	[GISK] (Billion Icelandic kr.)			[MEUR]
Alternative 1	14.268	1.849	16.117	**118.6**
Alternative 2	13.314	1.849	15.163	**111.6**
Alternative 3	17.706	1.849	19.555	**143.9**
Alternative 4	18.199	1.849	20.048	**147.5**
Alternative 5	20.140	0.274	20.414	**150.2**

Table 4.4 Construction costs for the five alternatives.

5 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 [20], [21] and as part of the Swiss Guideline [23]. Generally the Transit version with Norwegian data is used, but the use of the program has been adapted to Icelandic conditions and using the improved ventilation and evacuation model from the Swiss version.

In the present report the calculations have been carried out for the selected situations of ~2040. The results shall contribute to the basis for comparing the alternatives for extending the Hvalfjörður tunnel.

5.1 Accidents, Fires and Dangerous Goods Events

For each of the Alternatives 2, 3 and 5, the risk analyses are carried out and the results in terms of accidents, fires and events with dangerous goods are presented in terms of annual expected events, fatalities, injuries and rates normalising these figures in relation to the traffic in the tunnels. Some variants of the alternative are considered as well. The results are compared in the subsequent sections.

5.1.1 Hvalfjörður Alternative 2

The tunnel system consists of the existing tunnel tube for Northbound traffic and an adjacent new tube for the Southbound traffic. The new tube has basically the same alignment as the existing tunnel. Both tubes are operated with unidirectional traffic.

The summary of the results is shown in Table 5.1 and in Figure 5.1- Figure 5.6, which are illustrating the profile of accidents and fatalities along the tunnel alignment.

Hvalfjörður Tunnel, Alternative 2				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.0869	2.1330	1.5187	
Fires	0.0018	0.0151	2.3526	
Dangerous goods	0.0001	0.0003	0.0001	
Total	0.0888	2.148	3.871	
Traffic	32.14		Mill. veh-km/yr	
Accident rate	0.047		Per Mill. veh-km	
Fire rate	0.073		Per Mill. veh-km	
Fatality rate	2.76		Per Bill. veh-km	

Table 5.1 Alternative 2: Summary of estimated risk for ~2040.

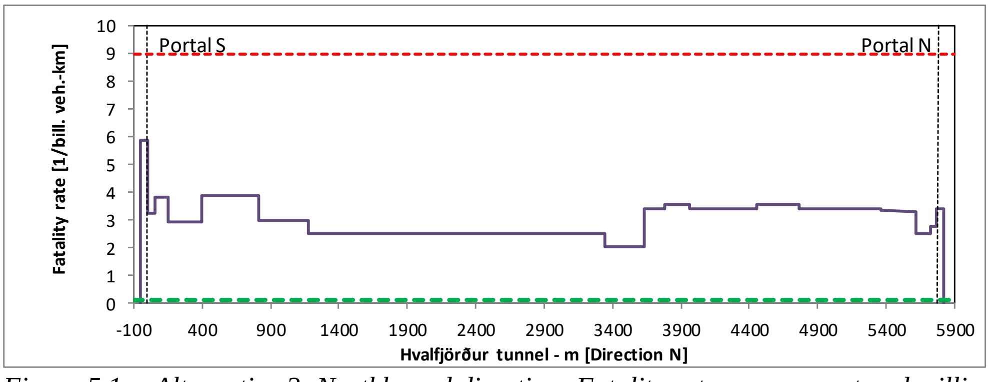


Figure 5.1 Alternative 2: Northbound direction: Fatality rate per segment and million vehicle km ~2040. North is to the right at the first axis.

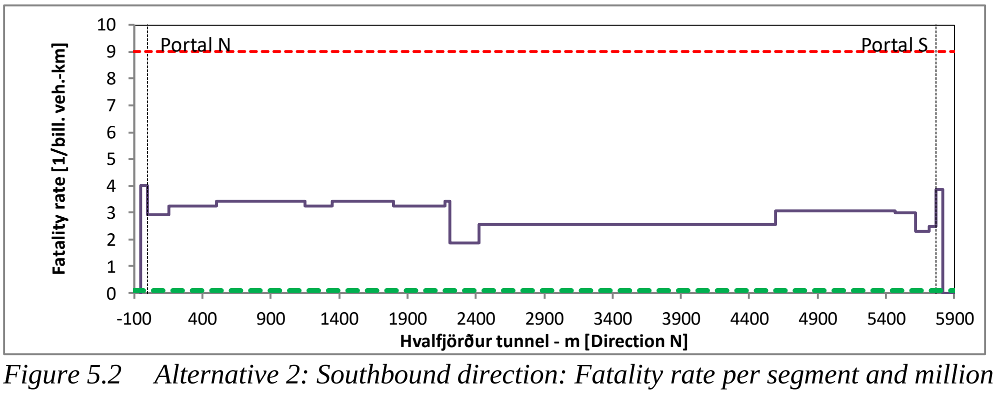


Figure 5.2 Alternative 2: Southbound direction: Fatality rate per segment and million vehicle km ~2040. South is to the right at the first axis.

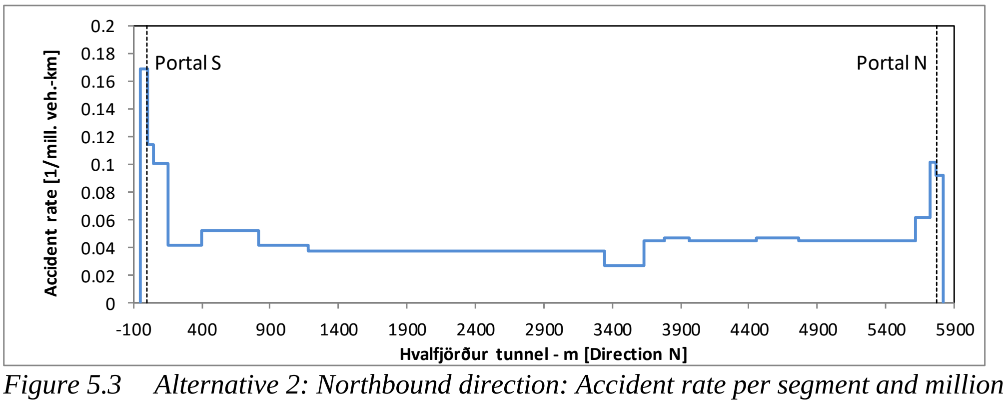


Figure 5.3 Alternative 2: Northbound direction: Accident rate per segment and million vehicle km ~2040. North is to the right at the first axis.

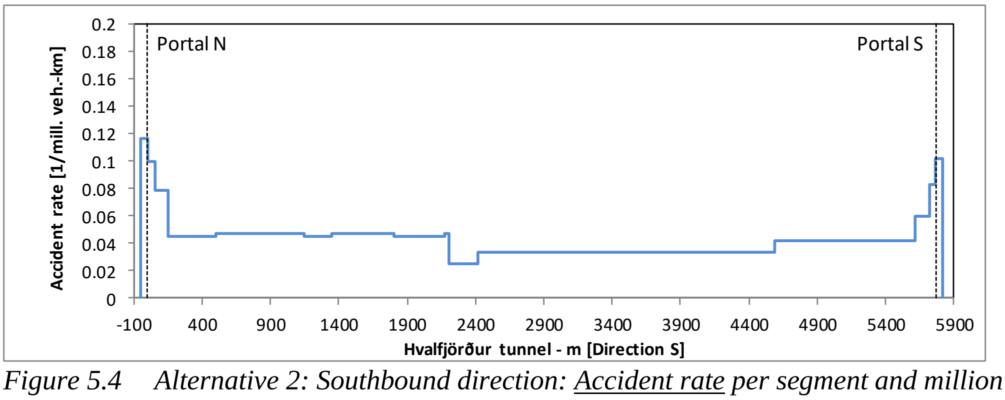


Figure 5.4 Alternative 2: Southbound direction: Accident rate per segment and million vehicle km ~2040. South is to the right at the first axis.

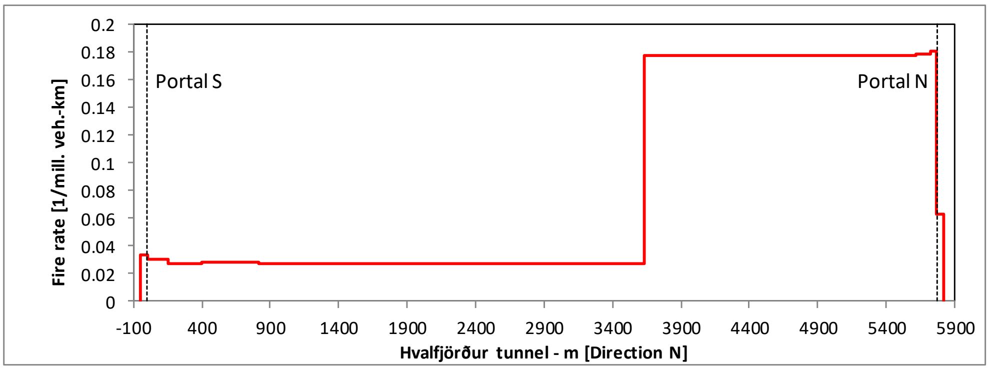


Figure 5.5 *Alternative 2: Northbound direction: Fire rate per segment and million vehicle km ~2040. North is to the right at the first axis.*

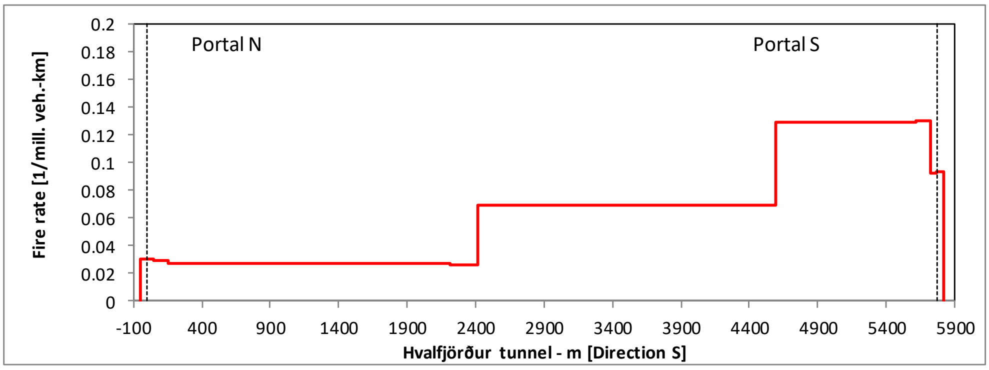


Figure 5.6 *Alternative 2: Southbound direction: Fire rate per segment and million vehicle km ~2040. South is to the right at the first axis.*

The risk resulting from events with dangerous goods is, even for unrestricted traffic, very low and contributes only 0.13% to the fatality risk and 0.02% for the injury risk. In Figure 5.7 and Figure 5.8 the results are shown as so-called F-N curves (shown here for the unrestricted transport of dangerous goods in ~2040), together with lower and upper limits from the Swiss regulation [23]. For curves under the lower limit, no special considerations of the transport of dangerous goods need to be carried out (according to Swiss regulation).

Figure 5.7 *Alternative 2: FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, northbound, ~2040.*

Figure 5.8 Alternative 2: FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, southbound, ~2040.

Investigations for Alternative 2: Wall Barriers

Barriers along the walls in the existing tube is an option in the tunnel expansion. Barriers would reduce the risk of injury accidents. It has been roughly assumed that the rough walls would lining of concrete barriers lead to an increase of 15% of the accidents and the consequences.

If this additional risk is removed from the Northbound tube in Alternative 2, the results corresponding to those presented in Table 5.1 as shown in Table 5.2.

Hvalfjörður Tunnel, Alternative 2 with wall barrier				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.0808	1.9799	1.4099	
Fires	0.0018	0.0151	2.3526	
Dangerous goods	0.0001	0.0003	0.0001	
Total	0.0827	1.995	3.762	
Traffic	32.14		Mill. veh-km/yr	
Accident rate	0.044		Per Mill. veh-km	
Fire rate	0.073		Per Mill. veh-km	
Fatality rate	2.57		Per Bill. veh-km	

Table 5.2 Alternative 2: Summary of estimated risk for ~2040 with wall barrier in the existing tunnel

With wall barriers in the Northbound existing tube, the fatality risk can be reduced by 0.0061 per year and the injury risk by 0.15 per year. Using the marginal costs of substitution of 3.0 million EUR per fatality and 0.1 million EUR per injury, the marginal reduction of risk can be quantified to 0.0337 Million EUR/yr.

With a structural life expectancy of 80 years, an annuity factor of 0.05103 (stemming from an annual rate of 5%) an inflation factor of 1.2187 (annual rate 1%) and assuming maintenance cost 1% of the investment costs, it can be determined that an investment of 53000 EUR would be in balance with the risk reduction. This would corresponds to 2x5770 m barrier @ 46 EUR/m.

Investigations for Alternative 2: Traffic direction

One of the specific questions which was requested to be answered was:

a) Is better to drive up or down on the 8% gradient on the north side?

In Alternative 2 presented above the Northbound traffic goes through the existing tunnel tube, which means that the traffic goes upwards at the 8% gradient. In the following the risk in the existing tunnel tube (without wall barrier) is compared for Northbound unidirectional traffic in the existing tube and Southbound unidirectional traffic in the existing tube.

In Table 5.3 and Table 5.4 the summary of results for unidirectional traffic in the existing tunnel tube is shown. In Table 5.3 the traffic is Northbound, in Table 5.4 the traffic is southbound. The traffic volume is the same in the two cases.

Hvalfjörður Tunnel, Existing tube, Northbound unidirectional traffic			
	Number killed / year	Number injured /year	Number events /year
Accidents	0.0409	1.0207	0.7254
Fires	0.00077	0.0075	1.3273
Dangerous goods	0.0001	0.0002	0.0000
Total	0.0417	1.028	2.053
Traffic	16.07		Mill. veh-km/yr
Accident rate	0.045		Per Mill. veh-km
Fire rate	0.083		Per Mill. veh-km
Fatality rate	2.60		Per Bill. veh-km

Table 5.3 Existing tube, Northbound unidirectional traffic: Summary of estimated risk for ~2040.

Hvalfjörður Tunnel, Existing tube, Southbound unidirectional traffic			
	Number killed / year	Number injured /year	Number events /year
Accidents	0.0412	1.0221	0.7283
Fires	0.00101	0.0077	1.0273
Dangerous goods	0.0001	0.0002	0.0000
Total	0.0422	1.030	1.756
Traffic	16.07		Mill. veh-km/yr
Accident rate	0.045		Per Mill. veh-km
Fire rate	0.064		Per Mill. veh-km
Fatality rate	2.63		Per Bill. veh-km

Table 5.4 Existing tube, Southbound unidirectional traffic: Summary of estimated risk for ~2040.

As expected, the number of accidents, and injuries and fatalities from accidents is approximately the same in the two cases. For fires, however, a significant difference can be noticed. The steep upwards gradient result in an increased number of fires, approximately 30% more fires are expected. On the other hand, the fires on a downwards part of a tunnel with unidirectional traffic may result in more severe consequences, because the smoke going up may flow over stopped vehicles. The expected number of fatalities is increased with about 30% in spite of the reduced number of fires.

In totality, the fatality rate is only modestly increased for the Southbound traffic going downwards on the steep part of the tunnel, but the conclusion may be that it is slightly better to use the existing tunnel tube for Northbound traffic.

For Alternative 2, also the new tunnel tube has a gradient of 8%, so the above observations may be of little importance.

One difference between Alternative 1 and Alternative 2 is the direction of the traffic. In Alternative 2 the existing tube is used for Northbound traffic whereas in Alternative 1 the new tube is used for Southbound traffic. In addition to this, Alternative 1 has a modified alignment where the maximum gradient is 7%. The resulting risks for Alternative 1 will be expected to be between those for Alternative 2 and Alternative 3, presumably closer to Alternative 2.

5.1.2 Hvalfjörður Alternative 3

The tunnel system consists of the existing tunnel tube for Southbound traffic and an new tube for the Northbound traffic. The new tube has a modified alignment with wider bends providing reduced gradients. Both tubes are operated with unidirectional traffic.

The summary of the results is shown in Table 5.5 and in Figure 5.9 - Figure 5.14, which are illustrating the profiles of accidents and fatalities along the tunnel alignment.

Hvalfjörður Tunnel, Alternative 3			
	Number killed / year	Number injured /year	Number events /year
Accidents	0.0920	2.3074	1.6294
Fires	0.0011	0.0138	2.0844
Dangerous goods	0.0001	0.0002	0.0000
Total	0.0932	2.321	3.714
Traffic	36.61	Mill. veh-km/yr	
Accident rate	0.045	Per Mill. veh-km	
Fire rate	0.057	Per Mill. veh-km	
Fatality rate	2.55	Per Bill. veh-km	

Table 5.5 Alternative 3: Summary of estimated risk for ~2040.

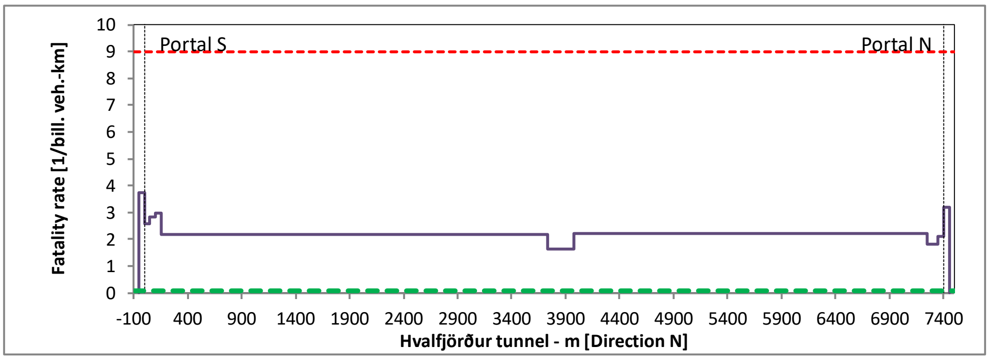


Figure 5.9 Alternative 3: Northbound direction: Fatality rate per segment and million vehicle km ~2040. North is to the right at the first axis.

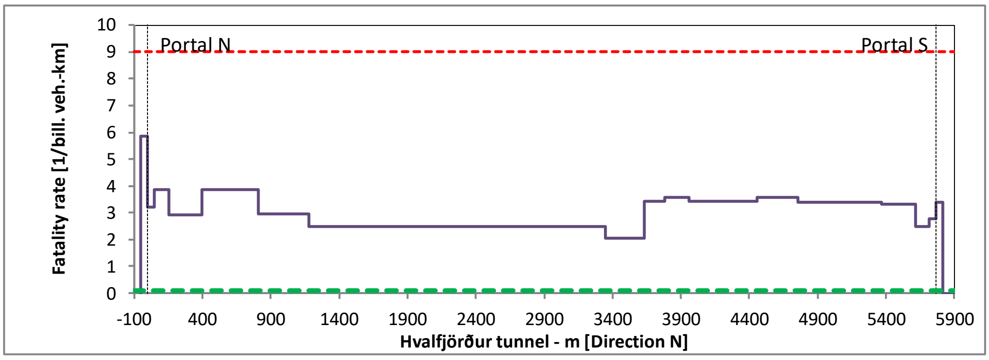


Figure 5.10 Alternative 3: Southbound direction: Fatality rate per segment and million vehicle km ~2040. South is to the right at the first axis.

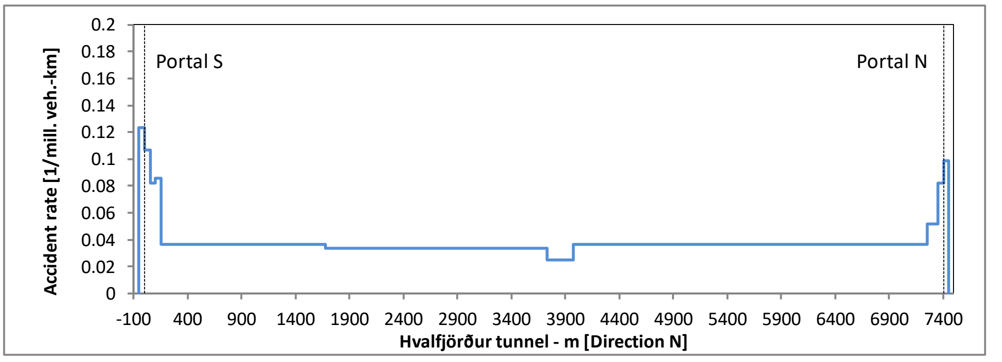


Figure 5.11 Alternative 3: Northbound direction: Accident rate per segment and million vehicle km ~2040. North is to the right at the first axis.

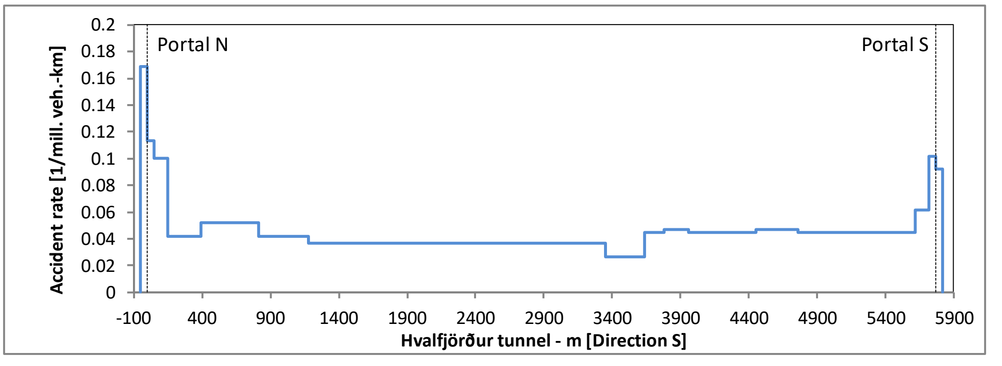


Figure 5.12 Alternative 3: Southbound direction: <u>Accident rate</u> per segment and million vehicle km ~2040. South is to the right at the first axis.

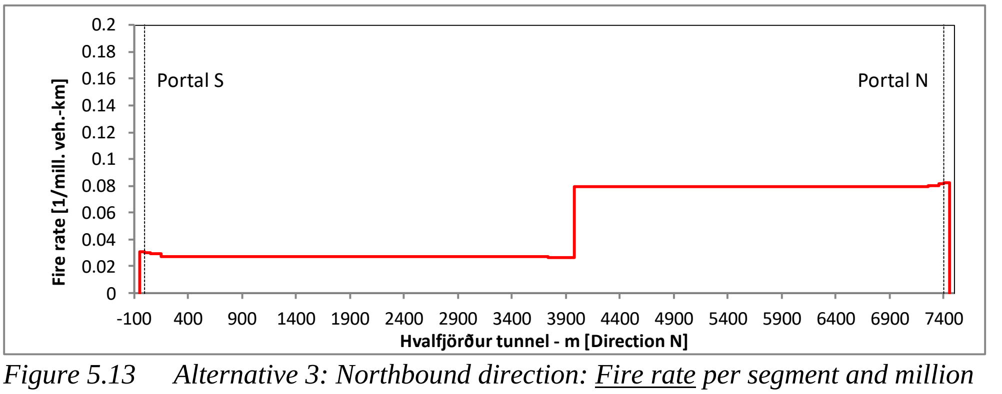


Figure 5.13 Alternative 3: Northbound direction: <u>Fire rate</u> per segment and million vehicle km ~2040. North is to the right at the first axis.

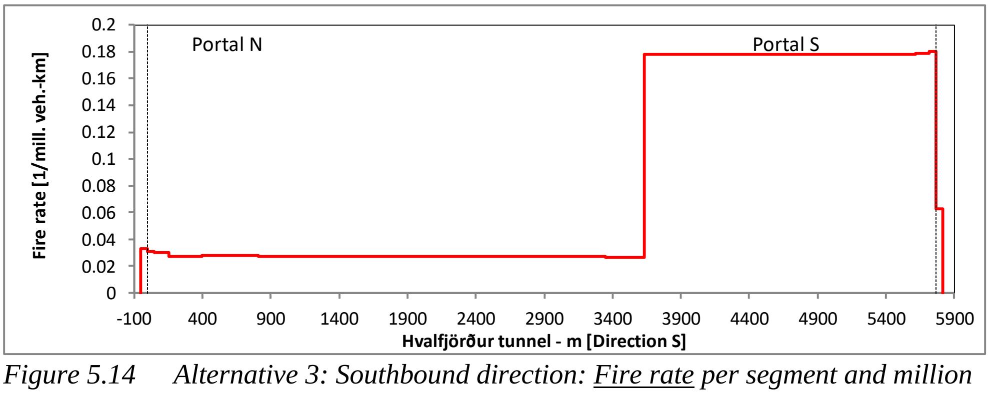


Figure 5.14 Alternative 3: Southbound direction: <u>Fire rate</u> per segment and million vehicle km ~2040. South is to the right at the first axis.

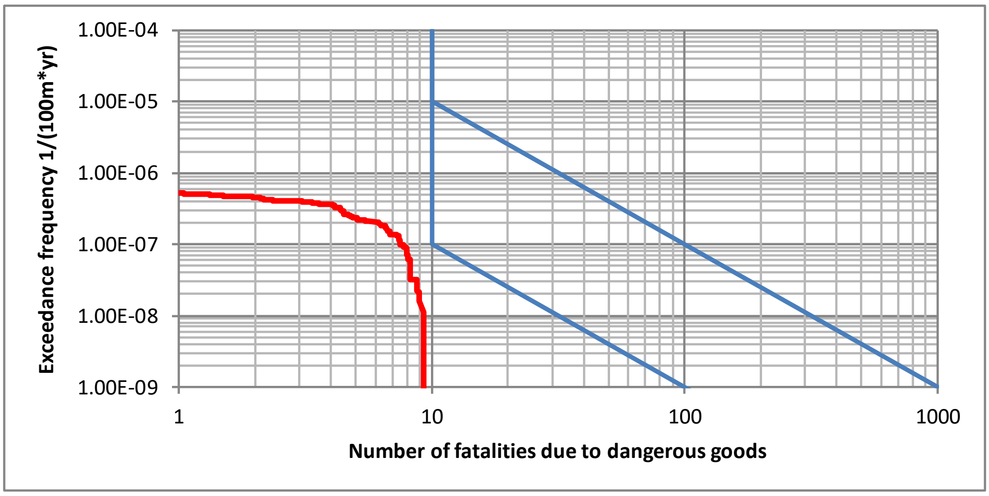


Figure 5.15 *Alternative 3: FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, northbound, ~2040.*

Figure 5.16 *Alternative 3: FN-curve for dangerous goods accidents. Fatalities per 100 m section per year, southbound, ~2040.*

Investigations for Alternative 3: Wall Barriers
Barriers along the walls in the existing tube is an option in the tunnel expansion. The evaluations of cost efficiency of wall barriers will not deviate significantly from the similar evaluations for Alternative 2.

5.1.3 Hvalfjörður Alternative 5

The new longer tunnel for Highway No. 1 facilitates the largest part of the traffic. For this traffic the new tunnel will provide a shorter driving distance. The present tunnel can then be used for traffic towards the community Akranes. Both tunnel tubes are operated in bi-directional traffic mode.

The summary of the results is shown for each tunnel separately in Table 5.6 and Table 5.7 and for both tunnels together in Table 5.8. In Figure 5.17 - Figure 5.22 the profiles of accidents and fatalities along the tunnel alignment are illustrated for both the new and the existing tunnel tube.

Hvalfjörður Tunnel, Alternative 5, Existing tunnel tube				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.0788	2.017	1.401	
Fires	0.0030	0.044	0.856	
Dangerous goods	0.0000	0.000	0.000	
Total	0.0819	2.062	2.257	
Traffic	11.25		Mill. veh-km/yr	
Accident rate	0.125		Per Mill. veh-km	
Fire rate	0.076		Per Mill. veh-km	
Fatality rate	7.28		Per Bill. veh-km	

Table 5.6 Alternative 5: Existing tunnel tube. Summary of estimated risk for ~2040.

Hvalfjörður Tunnel, Alternative 5, New tunnel tube				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.1139	2.858	2.026	
Fires	0.0080	0.076	1.443	
Dangerous goods	0.0008	0.002	0.000	
Total	0.1227	2.936	3.469	
Traffic	27.19		Mill. veh-km/yr	
Accident rate	0.075		Per Mill. veh-km	
Fire rate	0.053		Per Mill. veh-km	
Fatality rate	4.51		Per Bill. veh-km	

Table 5.7 Alternative 5: New tunnel tube. Summary of estimated risk for ~204.)

Hvalfjörður Tunnel, Alternative 5, Both tunnel tubes				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.1927	4.8751	3.427	
Fires	0.0110	0.1203	2.2985	
Dangerous goods	0.0008	0.0024	0.0001	
Total	0.2046	4.998	5.726	
Traffic	38.44		Mill. veh-km/yr	
Accident rate	0.089		Per Mill. veh-km	
Fire rate	0.060		Per Mill. veh-km	
Fatality rate	5.32		Per Bill. veh-km	

Table 5.8 Alternative 5: Total risk both tubes. Summary of estimated risk for ~2040.

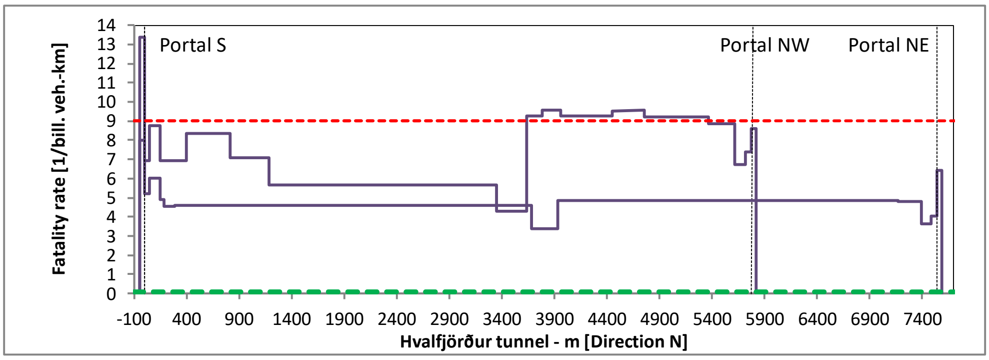


Figure 5.17 Alternative 5: Northbound direction: Fatality rate per segment and million vehicle km ~2040. North is to the right at the first axis.

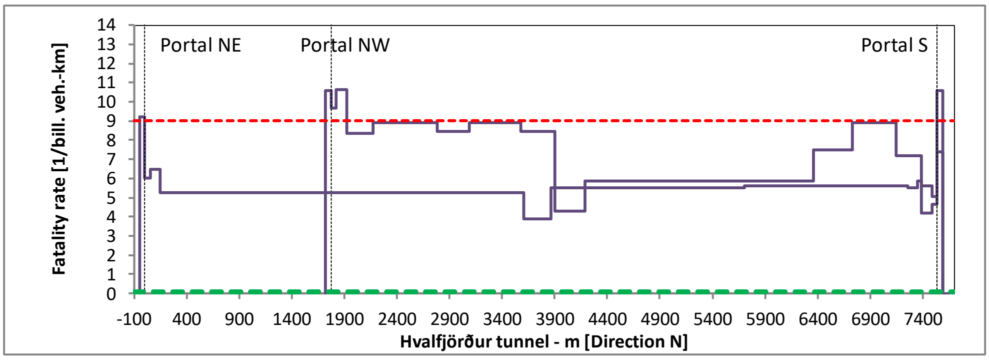


Figure 5.18 Alternative 5: Southbound direction: Fatality rate per segment and million vehicle km ~2040. South is to the right at the first axis.

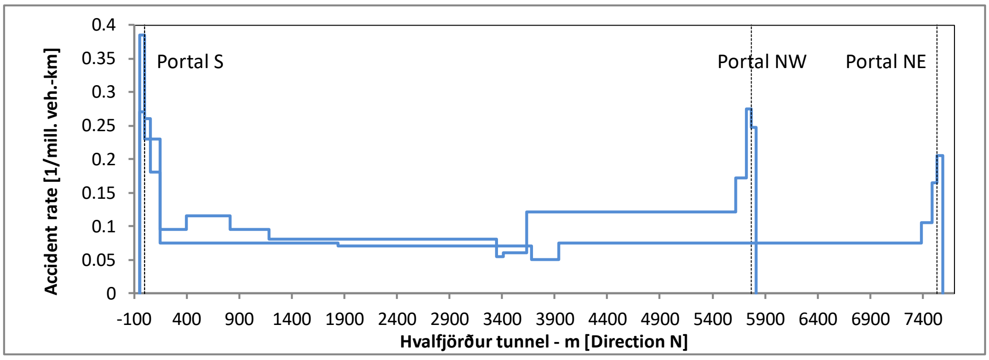


Figure 5.19 Alternative 5: Northbound direction: Accident rate per segment and million vehicle km ~2040. North is to the right at the first axis.

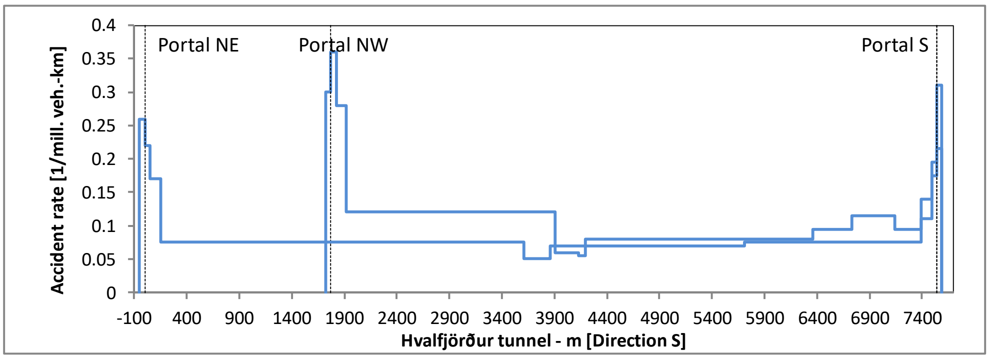


Figure 5.20 Alternative 5: Southbound direction: Accident rate per segment and million vehicle km ~2040. South is to the right at the first axis.

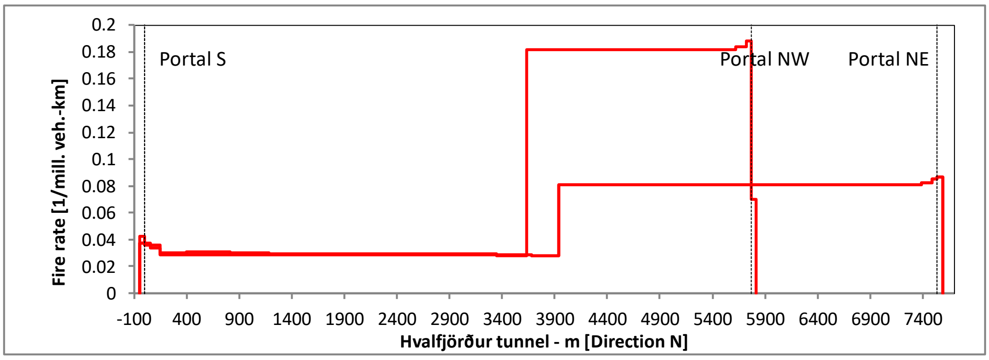


Figure 5.21 Alternative 5: Northbound direction: Fire rate per segment and million vehicle km ~2040. North is to the right at the first axis.

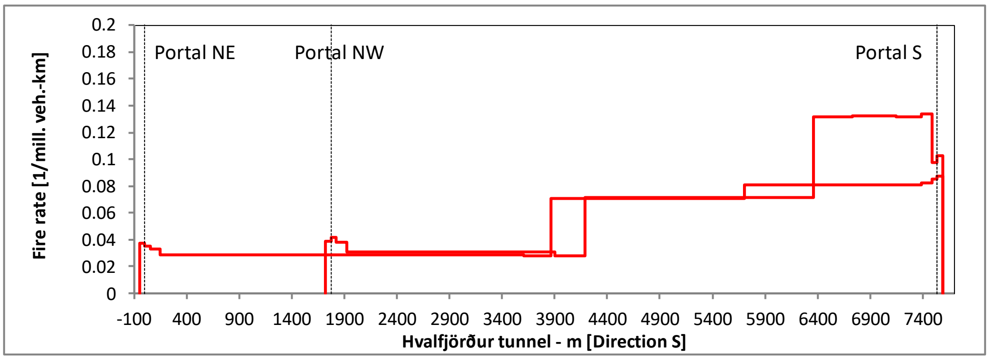


Figure 5.22 Alternative 5: Southbound direction: Fire rate per segment and million vehicle km ~2040. South is to the right at the first axis.

In Figure 6.2 - Figure 6.6 it is possible to compare the fatality-, accident- and fire rates for each direction of the two tunnel tubes. It is illustrated that the reduced gradients result in less accidents per vehicle-km, the reduced uphill gradients result in significantly reduced fire rates and the fatality rates are generally much lower in the new tube than in the upgraded existing tube.

Comparing the fatality-, accident- and fire rate of the existing tunnel tube in Figure 6.2 - Figure 6.6 to the rates in the existing tunnel tube without modifications in Figure 10.5 - Figure 10.10 it is illustrated that the safety measures and the reduced traffic has an effect.

As it can be seen in Table 5.6 - Table 5.8, the fatality rate in the existing tube is nearly halved compared to the existing tunnel tube without modification shown in Table 10.5 and is reduced to well below the upper limit. The fatality rate in the new tunnel tube is further reduced by 40%. In total, the estimated fatality rate for both directions and both tunnel tubes is 5.19 fatalities per billion veh-km, which is a significant reduction compared to the unmodified tunnel. However, the total fatality rate is considerably higher than for the solutions with unidirectional traffic.

Measured in annual expected consequences, the fatalities per year are approximately halved compared to the existing tunnel tube without modification shown in Table 10.5. Because the new tunnel tube is longer, the reduction in annual expected consequences is less pronounced than the fatality rate. The annual expected consequences of the alternatives with unidirectional traffic is significantly below those for Alternative 5.

Further comparison of the risk estimations of the tunnel systems can be found in the section below.

Investigations for Alternative 5: Wall Barriers

Barriers along the walls in the existing tube is an option in the tunnel expansion. Barriers would reduce the risk of injury accidents. It has been roughly assumed that the rough walls would lining of concrete barriers lead to an increase of 15% of the accidents and the consequences.

If this additional risk is removed from the existing tube in Alternative 5, the aggregated results for both tunnel tubes are as shown in Table 5.9.

Hvalfjörður Tunnel, Alternative 5 with wall barrier Both tunnel tubes				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.1825	4.612	3.245	
Fires	0.0110	0.1203	2.2985	
Dangerous goods	0.0008	0.0024	0.0001	
Total	0.1943	4.735	5.543	
Traffic	38.44		Mill. veh-km/yr	
Accident rate	0.084		Per Mill. veh-km	
Fire rate	0.060		Per Mill. veh-km	
Fatality rate	5.05		Per Bill. veh-km	

Table 5.9 Alternative 5: Total risk both tubes. Summary of estimated risk for ~2040 with wall barrier in the existing tunnel

With wall barriers in the Northbound existing tube, the fatality risk can be reduced by 0.0103 per year and the injury risk by 0.263 per year. Using the marginal costs of substitution of 3.0 million EUR per fatality and 0.1 million EUR per injury, the marginal reduction of risk can be quantified to 0.0572 Million EUR/yr.

With a structural life expectancy of 80 years, an annuity factor of 0.05103 (stemming from an annual rate of 5%) an inflation factor of 1.2187 (annual rate 1%) and assuming maintenance cost 1% of the investment costs, it can be determined that an investment of 90500 EUR would be in balance with the risk reduction. This would corresponds to 2x5770 m barrier @ 78 EUR/m.

The safety measure of a wall barrier is more cost efficient in Alternative 5 than in Alternative 2 and 3.

5.1.4 Comparison of risk estimates

	Hvalfjörður Tunnel		
	Fatalities /billion veh-km	Fatalities/year	Injuries/year
Existing tunnel without extension (for comparison)			
~2040	13.13	0.4221	9.64
Alternative 2			
~2040	2.76	0.0888	3.87
~2040 with wall barrier	2.57	0.0827	3.76
Alternative 3			
~2040	2.55	0.0932	3.71
~2040 with wall barrier	2.36	0.0871	3.61
Alternative 5			
~2040	5.32	0.2046	5.00
~2040 with wall barrier	5.05	0.1943	4.74

Table 5.10 Summary of the results of the risk estimations of the existing tunnel and Alternatives 2, 3 and 5.

All the above-mentioned alternatives provide a significant reduction of the fatality and injury risk. With Alternative 5, the annual expected number of fatalities in the tunnel is more than halved, and the number of injuries is nearly halved. The tunnel in Alternative 5 is longer than the existing tunnel, so the fatality rate in Alternative 5 is less than 40% of the exiting tunnel.. If a wall barrier is installed, the risk is reduced by further 5%.

For Alternative 5 it should be noticed that it is actually two tunnels which should be considered individually. The fatality rate in the existing tunnel tube is significantly higher than in the new tube. For the tunnel users only going to

Akranes, the improvement is safety will be less significant than indicated in the figures above.

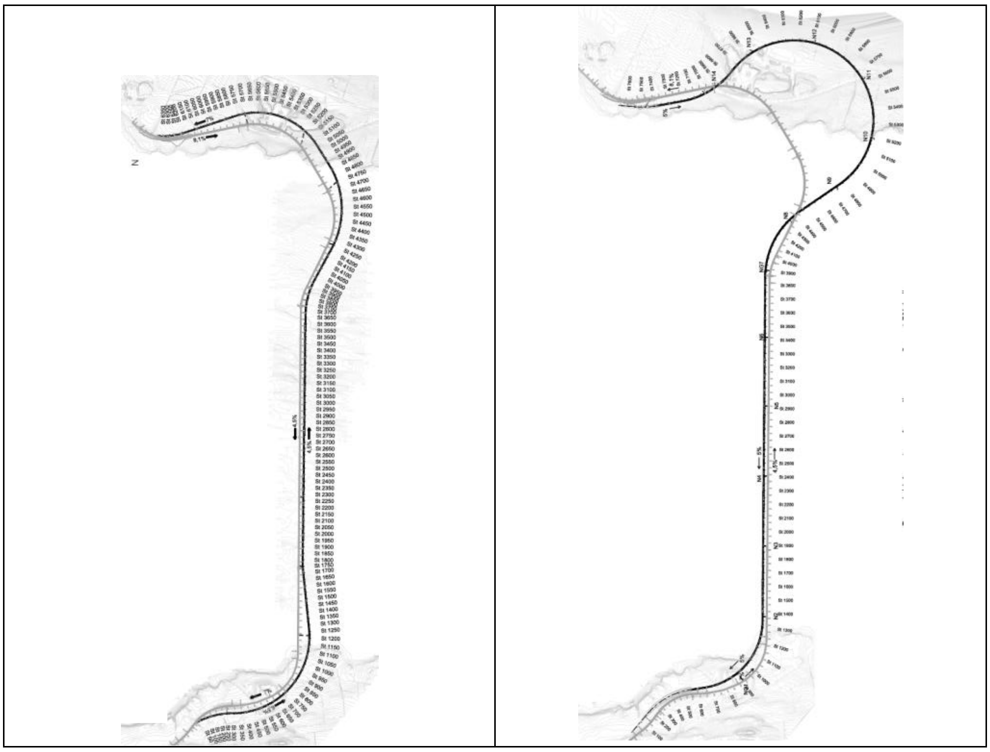
The northern portal of the new tube of Alternative 5 is not at the same location as the norther portal of the other tunnel alternatives, so a conclusion cannot be drawn on the tunnel risks alone. See section 6.1.

With Alternative 2 the risk is further reduced compared to Alternative 5. The number of fatalities are more than halved (reduced to 43%) compared to Alternative 5, the fatality rate is nearly halved (reduced to 52%) compared to Alternative 5. The difference in reduction of number of fatalities and the fatality rate is owing to the difference in length and traffic distribution in the two alternatives. The number of injuries is reduced to ¾ compared to Alternative 5. Compared to the existing tunnel the number of fatalities is reduced to less than ¼. If a wall barrier is installed a further 5% reduction can be achieved.

The key risk figures for Alternative 3 are very close to those of Alternative 2. The fatality rate is lower that for Alternative 2, but the annual estimate of fatalities is actually above the estimate for Alternative 2. This is owing to the longer tunnel in Alternative 3. See further discussion in section 6.1.

5.1.5 Other Alternatives (1, 4)

The Alternatives 1 and 4 have not been specifically modelled, calculated and assessed. In the following some analogy-considerations are made.



Route 1 **Route 4**

Figure 5.23 The alignment of two additional alternative routes: Alternative 1 and 4.

Alternative 1 consist of the existing tunnel tube for traffic in southbound direction and a parallel new tunnel tube in the northbound direction. The concept is close to Alternative 2, because the two tunnel tubes are parallel. The directions of the traffic in the two tubes are opposite Alternative 2 and the same as Alternative 3. The new tunnel tube has slightly reduced gradients (maximum 6.97%) and has for that reason wider turns on the slopes giver a longer distance. The turns are, however, not as wide as they are in Alternative 3. For that reason it may be concluded that the results would be between the calculated figures for Alternative 2 and Alternative 3, but closer to Alternative 2. The results from the calculations of Alternative 2 and 3 are very close anyway, so the results of the calculations for Alternative 2 may be a reasonably good estimate for Alternative 1.

Alternative 4 consist of the existing tunnel for northbound traffic and a new tunnel tube in the southbound direction. On the northern slope the new tunnel tube makes a wide turn similar to Alternative 3 in order to reduce the gradient (maximum 5%). The southbound tunnel tube crosses over the existing tunnel tube and is located on the eastern side of existing tunnel tube at the norther slope. On the southern part of the tunnel, the new tunnel tube follows an alignment close to the existing tunnel tube, i.e. similar to Alternative 2. It may be concluded that the alignment would give risk estimates between Alternative 2 and Alternative 3. The results from the calculations of Alternative 2 and 3 are very close anyway, so the mean value of results of the calculations for Alternatives 2 and 3 may be a reasonably good estimate for Alternative 4.

	Hvalfjörður Tunnel		
	Fatalities /billion veh-km	Fatalities/year	Injuries/year
Alternative 1			
~2040	2.74	0.0892	3.85
~2040 with wall barrier	2.55	0.0831	3.75
Alternative 4			
~2040	2.65	0.0910	3.79
~2040 with wall barrier	2.47	0.0849	3.69

Table 5.11 Crude valuation of the results of the risk estimations of Alternatives 1 and 4.

5.2 Traffic disturbance, stopped vehicles and detours

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 ~2040 and the above assumptions it is expected that the numbers of breakdowns for the various alternatives are indicated in Table 5.12.

	Hvalfjörður Tunnel		
	Number of stopped vehicles		Increase caused by gradients
	Low estimate	High estimate	
Alternative 2			
~2040	300	730	~90%
Alternative 3			
~2040	260	610	~40%
Alternative 5			
~2040 (exist. tube)	110	250	~90%
~2040 (new tube)	160	400	~20%
~2040 (both tubes)	270	650	~40%

Table 5.12 Estimated number of stopped vehicles in the tunnels per year

With the traffic volume used (corresponding to ~2040) stopped vehicles will occur in average every day - according to the calculations. The estimates include the 50 m in front and after the portals, but not the remaining part of the ramps. The gradients is an influencing factor resulting in an increase of the rates of 40% - 90%.

It should be noted that the rates of break-downs is based on data from the 1990'ies, and the development in vehicle technology until 2040 may influence the estimate.

Based on the general experience, the most common cause of break downs is motor stop (50% of the cases) followed by lack of fuel (25% of the cases). Furthermore, the general experience indicate that on ¼ - ⅓ of the broken-down vehicles will reach the lay-bys. The remaining vehicles may stop on the road lane and be an obstacle to the traffic. In particular in Alternative 5, which is operated in bi-directional traffic, stopped vehicles may be obstacles for the traffic flow. In Alternative 2 and 3, which have unidirectional traffic, the traffic flow would be less influenced.

Other traffic disturbances

In addition to accidents and stopped vehicles, also other events may disturb the traffic: for example maintenance and repair, exercises etc. These events can to some degree be planned, so that the disturbance is reduced to a minimum. Major repair and refurbishment may result in closure of the tunnel for a longer or shorter duration. In comparison to the existing single-tube tunnel, all the new tunnel configurations have the advantage that one tube can be closed and the traffic can be redirected to the adjacent tunnel for the duration of the closure.

If the redirection of the traffic is planned, then the new tunnel tubes for Alternatives 2 and 3 should be prepared for bi-directional traffic, even though this mode of operation is only used in exceptional cases. The existing tunnel tube is already prepared for bidirectional traffic. For Alternative 5, both tunnel tubes are always operated with bi-directional traffic.

6 General comparison of the alternatives

6.1 Traffic on open roads

The tunnels do not have the same lengths and the North-eastern portal of the new tube in Alternative 5 is not placed at the same location as the Northern portal of the other tunnel alternatives. In the following the implications on traffic volume and road accidents on the surface is considered.

The considerations are based on the assumption that 35% of the traffic is going to or from Akranes and 65% is going to or from Highway No. 1.

- The Southern reference points is 50 m outside the Southern Portal (boundary for the quantitative tunnel risk calculations) (point A in Figure 6.1)
- The North-western reference points is the roundabout / intersection between Highway No. 1 and Route 53 towards Akranes (485 m from the portal of the existing tunnel tube) (point B in Figure 6.1)
- The North-eastern reference point is the intersection between Highway No. 1 and Hléseyjarvegur (1350 m from the new tunnel in Alternative 5, and 5600 m from the roundabout / intersection between Highway No. 1 and Route 53, i.e. 6085 m from the North-western portal.) (point C in Figure 6.1).

Figure 6.1 Point A (Southern Portal), Point B (North-western Portal) and Point C (North-eastern Portal) shown for Alternative 5.

The surface traffic is estimated in Table 6.1 for the Alternatives 2, 3 and 5. The traffic is additional to the traffic in the tunnels in the three alternatives. The tunnel traffic is calculated in chapter 5 and stated in Table 5.1, Table 5.5, and Table 5.8. The total traffic comprising surface traffic and tunnel traffic is summarised in Table 6.2.

	NE to/from. Akranes	NW to/from Hwy No. 1	Both directions
	AADT [veh/day]		**Surface traffic [mill. Veh-km/yr]**
	5250	9750	
	Additional surface distance [km]		
Alternative 2	0.485	6.085	22.58
Alternative 3	0.485	6.085	22.58
Alternative 5	0.485	1.350	5.73

Table 6.1 Estimated surface traffic to/from the Northwest and the Northeast for Alternatives 2, 3 and 5.

	Both directions		
	Surface traffic [mill. Veh-km/yr]	**Tunnel traffic [mill. Veh-km/yr]**	**Total traffic [mill. Veh-km/yr]**
Alternative 2	22.58	32.14	54.72
Alternative 3	22.58	36.61	59.20
Alternative 5	5.73	38.44	44.17

Table 6.2 Estimated tunnel traffic, surface traffic and total traffic for Alternatives 2, 3 and 5.

Even though the tunnel traffic is higher in Alternative 5 than in the Alternatives 2 and 3, the surface traffic is much lower, because the tunnel serves the main traffic flow towards Highway No. 1 better than the two other alternatives. In total Alternative 5 saves 10 – 15 million veh-km per year compared to Alternatives 2 and 3.

The surface traffic will be considered with respect to traffic accidents and socio-economic costs in the sections below.

Traffic accidents on open roads

The additional traffic on the roads outside the tunnel may result in accidents which should be taken into account when comparing the safety of the tunnel alternatives. In order to estimate the number of injuries and fatalities of the three alternatives, the average rates in Table 2.8 are used. These rates represent the average rates of injury accidents and fatalities in the years 2010 – 2016. In addition, the average number of injuries per injury accident is estimated at 1.3 injuries/injury accident.

	Injury accidents	Fatalities	Injuries
	Rate per veh-km		**Rate per accident**
Rates	0.2297 E-06	4.12 E-09	1.3
	Estimate per year		
Alternative 2	5.187	0.0930	6.744
Alternative 3	5.187	0.0930	6.744
Alternative 5	1.317	0.0236	1.712

Table 6.3 Estimated fatalities and injuries caused by surface traffic to/from the Northwest and the Northeast for Alternatives 2, 3 and 5.

The consequences of accidents on the surface should be added to the consequence of accidents in the tunnels for comparison of the three alternatives, at it is shown in Table 6.4.

	Tunnel traffic		Surface traffic		Tunnel +Surface traffic	
	Fatalities /year	Injuries /year	Fatalities /year	Injuries /year	Fatalities /year	Injuries /year
Existing tunnel without extension (for comparison)						
~2040	0.4221	9.64	0.0930	6.744	0.5151	16.384
Alternative 2						
~2040	0.0888	3.87	0.0930	6.744	0.1818	10.614
~2040 w/wallb.	0.0827	3.76	0.0930	6.744	0.1757	10.504
Alternative 3						
~2040	0.0932	3.71	0.0930	6.744	0.1862	10.454
~2040 w/wallb.	0.0871	3.61	0.0930	6.744	0.1801	10.354
Alternative 5						
~2040	0.2046	5.00	0.0236	1.712	0.2282	6.712
~2040 w/wallb.	0.1943	4.74	0.0236	1.712	0.2179	6.452

Table 6.4 Summary of the results of the risk estimations of the existing tunnel and Alternatives 2, 3 and 5. Total based on contributions from traffic in the tunnels and on roads on the surface.

The surface traffic is the same in Alternatives 2 and 3, hence, these alternatives are very close also when the consequences of surface accidents are added. Alternative 5 has a significantly higher number of fatalities in the tunnel than Alternatives 2 and 3. In total including tunnel traffic and surface traffic, the number of fatalities is still higher than for Alternative 2 and 3. However, the total number of injuries for tunnel traffic and surface traffic) in Alternative 5 is much lower than in Alternative 2 and 3.

In Table 6.5 the improvements of Alternatives 2, 3 and 5 compared to the existing tunnel are stated in terms of injuries and fatalities per year. In addition the improvements are multiplied with the marginal costs of 3 MEUR per fatality and 0.1 MEUR per injury (see also chapter 3). These values can be considered as the safety-related benefits of the alternatives.

	Improvements Surface and tunnel traffic		Benefits /year using marginal costs [MEUR/year]		
	Fatalities /year	Injuries /year	Fatalities	Injuries	Total
Existing tunnel without extension (for comparison)					
~2040	0	0	0	0	0
Alternative 2					
~2040	0.3333	5.770	0.9999	0.5770	1.5769
~2040 w/wallb.	0.3394	5.880	1.0182	0.5880	1.6062
Alternative 3					
~2040	0.3289	5.930	0.9867	0.5930	1.5797
~2040 w/wallb.	0.3350	6.030	1.0050	0.6030	1.6080
Alternative 5					
~2040	0.2869	9.672	0.8808	0.9672	1.8280
~2040 w/wallb.	0.2972	9.932	0.8917	0.9932	1.8849

Table 6.5 improvements of Alternatives 2, 3 and 5 compared to the existing tunnel are stated in terms of injuries and fatalities per year and as safety-related benefits using 3 MEUR per fatality and 0.1 MEUR per injury.

The results of this consideration is that the safety related benefit is slightly larger for Alternative 5 than for the Alternatives 2 and 3. A large part of this benefit comes from a reduction of the traffic on the roads outside the tunnel.

Socio-economic costs of the traffic.
The difference in traffic shown in Table 6.2 also has direct socio-economic costs. The shorter distance compared to the existing tunnel (and time used by

the tunnel users) is considered a benefit, and with a capitalisation of 0.90 EUR per veh-km, the benefits of the Alternatives 2, 3 and 5 compared to the existing tunnel is shown in Table 6.6.

	Annual traffic reduction Total traffic [mill.veh-km]	Traffic benefits [MEUR/year] using marginal costs
Existing tunnel without extension (for comparison)		
~2040	0	0
Alternative 2		
~2040	0	0
~2040 w/wallb.	0	0
Alternative 3		
~2040	-4.47	-4.023
~2040 w/wallb.	-4.47	-4.023
Alternative 5		
~2040	10.55	9.496
~2040 w/wallb.	10.55	9.496

Table 6.6 Traffic improvements of Alternatives 2, 3 and 5 compared to the existing tunnel are stated in terms of traffic reduction in mill. veh-km and socio-economic benefits in terms of MEUR/yr]

With respect to traffic Alternative 2 has no benefits or disadvantages compared to the existing tunnel. Alternative 3 has a disadvantage because the driving distance between the portals at point A and B is longer for the new tunnel tube. On the other hand Alternative 5 provides a shorter driving distance for the majority of the traffic.

With the use of the capitalisation of 0.90 EUR per veh-km, the benefit of the reduced traffic / vehicle-km becomes a dominating part of the comparison. Considering only safety in the tunnel and on the roads outside, the benefits are relatively close (as it can be seen in Table 6.5). Adding the traffic-related benefits in Table 6.5, Alternative 3 turns out to have a negative benefit and the benefit of Alternative 5 is more than 6 times higher than for safety alone. (see also chapter 7)

6.2 Detours as consequence of accidents, maintenance etc.

If the new tunnel tubes in Alternatives 2 and 3 are not prepared for bidirectional traffic then a closure of the existing tube would result in a (73.1 km – 8.1 km =) 65 km detour around the fjord, which according to google maps will take additionally (59 min – 9 min) = 50 min. These values are relevant for the 35% of the traffic going to Akranes, for the 65% of the traffic going further North along Highway No. 1, the closure of the existing tube would result in a (61.3 km – 20.0 km =) 41.3 km detour around the fjord, which according to google maps will take additionally (51 min – 18 min) = 33 min. The weighted average is a 50 km detour using 39 min.

For each day of closure this will be additionally 375000 veh-km/day and 4875 vehicle-hours, with in average 1.2 persons per vehicle, it will be 5850 person-hours/day. The time consumption may be more than this, because the traffic on the detour may result in slower traffic than in the normal conditions.

If these values are capitalised with 0.90 EUR per veh-km, then the disadvantage of not preparing the new tunnels for bi-directional traffic will be 0.338 MEUR/day of closure. Say, the existing tunnel tube is closed for a month due to major refurbishment then the societal traffic costs would be 10 MEUR. If in average the tunnel tube is closed 5 days per year it will result societal traffic costs of 1.7 MEUR. With a structural life expectancy of 25 years, an annuity factor of 0.07095 (stemming from an annual rate of 5%) an inflation factor of 1.1021 (annual rate 1%) and assuming maintenance cost 1% of the investment costs, it can be determined that an investment of 20.75 MEUR would be in balance with the risk reduction of 1.7 MEUR per year. It may be assumed that the construction costs for the preparation for bidirectional traffic is significantly below 20 MEUR, and even if the estimation of closure is uncertain the preparation seems to be cost efficient.

6.3 Gradients

The maximum gradients in the Alternatives 1-5 are shown in Table 6.7:

	Existing tube	New tube	Comment
Alternative 1	8.09%	6.97%	Unidirectional, traffic distribution 50/50
Alternative 2	8.09%	8.09%	
Alternative 3	8.09%	5.01%	
Alternative 4	8.09%	5.00%	
Alternative 5	8.09%	5.00%	Bi-directional, traffic distribution 35/65

Table 6.7 Maximum gradients in the 5 alternatives.

In the EU directive 2004/54/EC [13] it is stated that:

"2.2. Tunnel geometry … 2.2.2. Longitudinal gradients above 5 % shall not be permitted in new tunnels, unless no other solution is geographically possible.
2.2.3. In tunnels with gradients higher than 3 %, additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis."

Similarly, in the Norwegian standard HB N500 [14], the following requirement is stated:

"3.2.3 Vertikalkurvatur … Tunnel skal bygges med stigning ≤ 5 %. Det fremgår av Tunnelsikkerhetsforskriftenes Vedlegg I, at det for tunneler med stigning på mer enn 3 % skal treffes ekstra og/eller forsterkede tiltak for å forbedre sikkerheten på grunnlag av en risikoanalyse. Slike ekstra / forsterkede tiltak er innarbeidet i normalkravene."

The requirements in the EU directive and the Norwegian handbook are coinciding and do not permit new tunnels with gradients above 5.0%. Refurbishment of existing tunnels with respect to the gradients is not possible and is not required and restrictions to traffic in these tunnels are also not mentioned.

It may be discussed whether the extension of the Hvalfjörður Tunnel shall be considered a "new tunnel" or an improvement of the existing tunnel. If it is regarded a new tunnel, then Alternative 2 (and Alternative 1) are not fulfilling the requirements, because the new tube has a maximum gradient of 8.09% (Alt.1: 6.97%), which is significantly above 5.0%. However, as shown in the results of the risk analyses in section 5.1.1 (and 5.1.5), the extension is definitely an improvement.

In Alternative 5, the existing tunnel tube is upgraded and operates as a separate tunnel. The new tube is a tunnel in it own right. It is clear that the existing tunnel can continue its operation, even though the gradient is over 5 %. The new tunnel does respect the requirement of a maximum gradient of 5 %. This extension alternative is with no doubt respecting the requirements of the regulation.

With respect to fulfilment of the directive Alternative 3 (and 4) lie between Alternative 2 and 5: the maximum gradient of the new tube is 5 % and in keeping with the requirement. However it may be discussed whether the new tunnel system with unidirectional traffic in two tubes can be regarded as a “new tunnel” or an improvement of the existing tunnel. Only if it can be regarded as an improvement of the existing tunnel, the tunnel system is in keeping of the directive and handbook.

It is assumed that the extension in Alternatives 1- 4 can be considered improvements of an existing tunnel and thereby fulfilling the requirements of the directive 2004/54/EC and HB N500. Alternative 5 is with no doubt respecting the requirements.

6.4 Exits, Cross passages, emergency rooms

Distances

All five alternatives have exits for each 500 m, which is in keeping with the requirements in 2004/54/EC [13]:

> *“2.3.8. Where emergency exits are provided, the distance between two emergency exits shall not exceed 500 metres.”*

In HB N500 [14], emergency exits are required for single tube tunnels (with bi-directional traffic, if AADT is over 8000 veh/day and shall be considered for AADT between 4000 and 8000 veh/day. For a tunnel with an AADT of 15000 veh/day and for a 7.5 km long tunnel with an AADT of 9750 veh/day (new tunnel tube of Alternative 5), the tunnel shall be constructed with two tunnel tubes, unidirectional traffic and exits through cross passages for each 250 m:

> “*For toløps tunneler etableres nødutganger med gangbare tverrforbindelser mellom tunnelløpene med innbyrdes avstand på 250 meter.”*

According to the classification in HB N500 [14], Alternative 2 and 3 is in class E and should be configurated as two tunnel tubes with unidirectional traffic and with cross passages each 250 m. If Alternative 5 is considered as two individual tunnels, the new tunnel (7.54 km long with an AADT of 9750 veh/day) should itself be built with two tunnel tubes and cross passages every 250 m. For the existing tunnel tube in Alternative 5 (5.77 km long with an AADT of 5250 veh/day) emergency exits can be considered according to HB N500 [14].

The configuration of the emergency exits does not fulfil the requirements of the Norwegian standard in any of the alternatives. In Alternative 5 the configuration of the tunnel tubes does not fulfil the requirements either.

Design requirements for emergency exits

The design of the emergency exits are further described in 2004/54/EC [13] and HB N500 [14]:

The purpose is described in 2004/54/EC [13]:

> *“2.3.3 Emergency exits allow tunnel users to leave the tunnel without their vehicles and reach a safe place in the event of an accident or a fire and also provide access on foot to the tunnel for emergency services. Examples of such emergency exits are:*
> *- direct exits from the tunnel to the outside,*
> *- cross-connections between tunnel tubes,*
> *- exits to an emergency gallery,*
> *- shelters with an escape route separate from the tunnel tube.*

And it is further stated that:

2.3.4. Shelters without an exit leading to escape routes to the open shall not be built.
2.3.6. In any event, in new tunnels, emergency exits shall be provided where the traffic volume is higher than 2 000 vehicles per lane.
2.3.7. In existing tunnels longer than 1 000 metres, with a traffic volume higher than 2 000 vehicles per lane, the feasibility and effectiveness of the implementation of new emergency exits shall be evaluated.

For the paragraph 2.3.6, Norway has obtained an exemption, increasing the value to 4000 vehicles per lane, i.e. AADT = 8000 veh/day.

The design requirements for emergency exits in HB N500 indicate: "*For ettløps tunneler kan nødutganger etableres med utganger direkte til det fri, utganger til rømningstunnel eller ved bygging av ekstra tunnelløp med gangbare tverrforbindelser mellom tunnelløpene.*"

And it is further stated that:

- *Helningsgraden på nødutgangen skal ikke være brattere enn maksimalt 5 %...*

Emergency exits in the alternatives

The types of emergency exits in Alternatives 1 – 5 are summarised in Table 6.8.

	Type 1 **Cross passages** **≤ 5% inclination**	**Type 2** **Exit with staircase**	**Type 3** **Emergency room**
Alternative 1	6	5	-
Alternative 2	11	-	-
Alternative 3	7	-	7
Alternative 4	2	5	7
Alternative 5	6	-	8

Table 6.8 Summary of emergency exits in Alternatives 1 – 5.

For Alternative 2, all emergency exits are designed as cross passages between the existing and the new tube. All cross passages are designed with a slope less than 5%. This is all in accordance to the requirements from 2004/54/EC [13] and HB N500 [14] mentioned above, except the maximum distance of 250 m mentioned in HB N500 (but not in 2004/54/EC).

In Alternatives 3 and 5 approximately half of the emergency exits are emergency rooms, which are formally violating the purpose of providing access on foot to the tunnel for emergency services, and the statement in 2.3.4 "*Shelters without an exit leading to escape routes to the open shall not be built.*". HB N500 also formally does not allow for emergency rooms without escape routes to the open. For Alternative 3, the distance of 500 m is above the maximum 250 m mentioned in HB N500. If Alternative 5 is considered as two individual tunnels, the emergency exits in the existing tunnel tube may be regarded as compliant with the regulation, because it is an improvement of the existing tunnel, and it is only required to study the feasibility and effectiveness of new exits. For the AADT of 5250 veh/day and a tunnel with bidirectional traffic the distance of 500 m between the exits is acceptable both with reference to 2004/54/EC and HB N500. However, the new tunnel tube, regarded as a separate tunnel, does not respect the requirements for emergency exits.

Alternatives 1 and 4 have less cross passages and instead some exits with staircases, which do not resect the requirement of an inclination of maximum 5%, and give less favourable conditions for escape for mobility impaired persons. In addition the staircases do not provide the same easy access for the emergency services as the cross passages with ≤ 5% inclination.

Emergency rooms in general

Emergency rooms have been discussed in general in [25] and specifically for an existing tunnel in [12]. In [25] "*Shelters or emergency exits every 500 m*" were recommended for tunnels over 3 km or with AADT over 4000 veh/day. In more detail, it was stated:

For etløbstunneler vil det ofte være vanskeligt og forbundet med store omkostninger at etablere udgange til det fri. Passende dimensionerede og indrettede tilflugtsrum kan dog yde den samme sikkerhed som nødudgange til det fri. ... EU-direktivets tager forbehold mod tilflugtsrum, men der gives mulighed for nyskabende teknik. Tilflugtsrum synes dog i alle tilfælde at være bedre end slet ikke at have nogen nødudgange . *Tilflugtsrummene bruges indtil de nødstedte trafikanter aktivt kan reddes ud af tunnelen.*	*For single tube tunnels establishing exits to the outside is often difficult and associated with high costs. Suitably designed and equipped shelters may, however, provide the same safety as exits to the outside. ... The EU directive takes reservations against shelters but opens up for innovation and new technology. Shelters appears in any case to be better than the situation without any exits. The shelters can be used until the distressed tunnel users can be actively rescued.*

Table 6.9 Quote from NordFoU [25]: "Evakuering i vegtunneler" (original and translation)

According to Directive 2004/54/EC implementation of shelters are discouraged (see above). For Nordic conditions the statement in 2004/54/EC may be too crude, because a well-designed shelter is better than no exit at all, - and exits to the open in many Nordic tunnels are unrealistically expensive.

The opening for using shelters is the statement in the directive concerning innovative techniques:

Derogation for innovative techniques *1. In order to allow the installation and use of innovative safety equipment or the use of innovative safety procedures which provide an equivalent or higher level of protection than current technologies, as prescribed in this Directive, the administrative authority may grant a derogation from the requirements of the Directive on the basis of a duly documented request from the Tunnel Manager.*
2. If the administrative authority intends to grant such a derogation, the Member State shall first submit a derogation application to the Commission containing…

The directive also says:

(15) An exchange of information on modern safety techniques ... between the Member States should be systematically organised.
(20) Further technical progress is still necessary to improve tunnel safety. A procedure should be introduced to allow the Commission to adapt the requirements of this Directive to technical progress

In the future it may be accepted to use emergency rooms based on the experience in Iceland and Norway. Good experience with designing, implementing and testing shelters in existing tunnels has been achieved [12]. Also, a positive reception of the concept from the fire brigade can be recognised.

For the time being, the situations seems to be that the construction of emergency rooms instead of emergency exits have not gained general acceptance. In terms of the risk analyses, however, it is assumed that the same safety for the evacuating passengers can be achieved if the emergency rooms are designed as a safe haven for a suitable long time and the evacuation and rescue is planned in detail in the safety plan and accepted by the emergency services.

7 Summary, conclusion and risk evaluation

The risk has been estimated by using a standardised model for quantitative risk analyses. The risk has been estimated for the traffic situation for ~2040.

7.1 Risk evaluation

Evaluation of fatality rate

An upper limit for the fatality rate has been established in section 3.1. In the hypothetical situation of the existing tunnel with the traffic of AADT = 15000 (corresponding to ~2040), the fatality rate will be over 13 fatalities per billion veh-km, which is way over the limit. For all the investigated alternatives, the fatality rates are reduced significantly compared this hypothetical situation, and are under the upper limit, inside the ALARP zone. The fatality rates are shown in Table 7.1 and illustrated in Figure 7.1.

	Fatalities /billion veh-km	Total costs for construction and refurbishment [MEUR]
Existing tunnel without extension	13.13	-
Alternative 2	2.76	111.6
Alternative 3	2.55	143.9
Alternative 5	5.32	150.2
Alternative 5 New tube	4.51	
Alternative 5 Existing tube	7.28	

Table 7.1 Summary: fatality rates of the existing tunnel and Alternatives 2, 3 and 5 as well as the total costs for construction and refurbishment

With wall barriers the fatality rates can be reduced further with approximately 0.2 – 0.3 fatalities/billion veh-km.

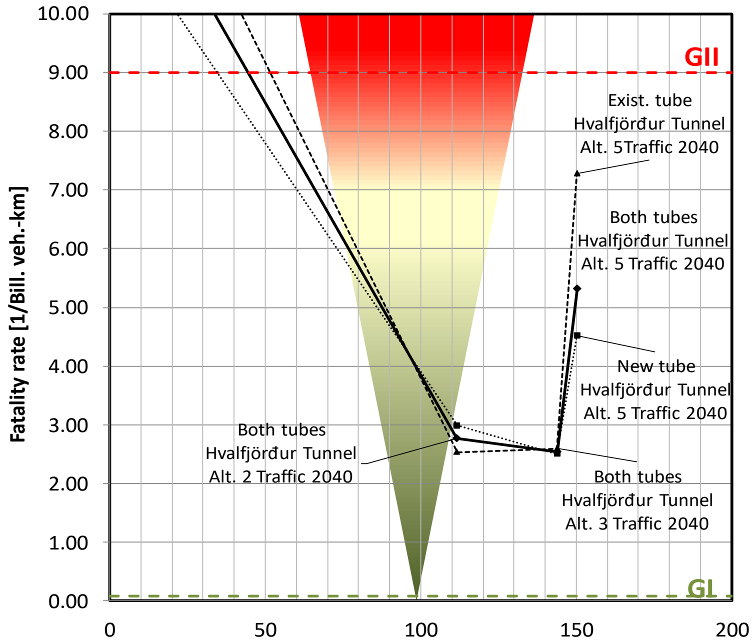


Figure 7.1 Fatality rates for the Alternatives 2, 3 and 5, the ALARP zone and the upper and lower limits.

The investment of 111.6 MEUR reduces the fatality rate to a low level in the ALARP zone. The additional investment of 32 MEUR results in a very limited reduction of the fatality rate. Alternative 5 is only 6 MEUR more expensive than Alternative 3, but the configuration with bi-directional traffic result in a higher fatality rate.

For Alternative 5, the traffic going to and from Akranes, using the existing tunnel, will experience a much higher fatality rate than in the other alternatives, and for this part of the population, Alternative 5 is less beneficial than the other alternatives. Also the traffic in the new tunnel tube in Alternative 5 will be exposed to a higher fatality rate than in the other alternatives. However, the traffic using the new tunnel tube going in the direction of Highway No. 1 will have other benefits of the new tunnel system as discussed in the following sections.

Evaluation of fatality and injury risk

The estimated risk of fatalities per year the picture gives the same trend as the fatality rates, and are illustrated in the two first columns in Table 7.2: whereas a hypothetical existing tunnel without extension would be expected to result (in average, ~2040) in 0.42 fatalities per year, Alternatives 2 and 3 reduce this figure to approximately 0.09 per year, and the estimated fatalities in Alternative 5 is around 0.20 per year. For the injuries, the improved extended alternatives also reduce the risk, but not quite as much as for the fatality risk.

With wall barriers the fatality can be reduced further with approximately 0.06 – 0.10 fatalities/year and 0.1 – 0.25 injuries per year.

	Tunnel traffic		Surface traffic		Tunnel +Surface traffic	
	Fatalities /year	Injuries /year	Fatalities /year	Injuries /year	Fatalities /year	Injuries /year
Existing tunnel	0.4221	9.64	0.0930	6.744	0.5151	16.384
Alternative 2	0.0888	3.87	0.0930	6.744	0.1818	10.614
Alternative 3	0.0932	3.71	0.0930	6.744	0.1862	10.454
Alternative 5	0.2046	5.00	0.0236	1.712	0.2282	6.712

Table 7.2 Summary of the results of the risk estimations of the existing tunnel and Alternatives 2, 3 and 5. Total based on contributions from traffic in the tunnels and on roads on the surface.

Alternative 5 reduces the traffic on the surface compared to the other alternatives. In the third and fourth column in Table 7.2 the results of estimations of fatalities and injuries on the roads on the surface between three reference points are reported: The reduced traffic on the North-shore of Hvalfjörður in Alternative 5 result in significantly less accidents, injuries and fatalities than for the other alternatives. In total (the fifth and sixth column in Table 7.2) the estimated number of fatalities lie within ~+/-20%, and the total number of fatalities are lower for Alternative 5 than for the other alternatives.

This conclusion is based on a rather crude estimation of the risk on the open roads, using average rates of injuries and fatalities on rural road in Iceland, and possibly that part of the analysis could be further detailed.

In Table 7.3 the improvements of Alternatives 2, 3 and 5 compared to the existing tunnel are stated in terms of injuries and fatalities per year. In addition the improvements are multiplied with the marginal costs of 3 MEUR per fatality and 0.1 MEUR per injury (marginal costs ref. section 3.1). These values can be considered as the safety-related benefits of the alternatives.

	Improvements /year Surface and tunnel traffic		Safety benefits /year using marginal costs [MEUR/year]			Total costs for construction and refurbishment [MEUR]
	Fatalities	Injuries	Fatalities	Injuries	Total	
Existing tunnel	0	0	0	0	0	-
Alternative 2	0.3333	5.770	0.9999	0.5770	1.5769	111.6
Alternative 3	0.3289	5.930	0.9867	0.5930	1.5797	143.9
Alternative 5	0.2869	9.672	0.8808	0.9672	1.8280	150.2

Table 7.3 improvements of Alternatives 2, 3 and 5 compared to the existing tunnel are stated in terms of injuries and fatalities per year and as safety-related benefits using 3 MEUR per fatality and 0.1 MEUR per injury.

The results of this consideration is that the safety related benefit is slightly larger for Alternative 5 than for the Alternatives 2 and 3. A large part of this benefit comes from a reduction of the traffic on the roads outside the tunnel.

By means of annuity and inflation rates, the construction costs (additional costs compared to the existing situation) are calculated:

With a structural life expectancy of 80 years, an annuity factor of 0.05103 (stemming from an annual rate of 5%) an inflation factor of 1.2187 (annual rate 1%) and assuming maintenance cost 1% of the investment costs, the annual costs of the three alternatives can be determined, as shown in Table 7.4.

	Total safety benefits /year using marginal costs [MEUR/year]	Annual total costs for construction and refurbishment [MEUR/year]	Safety benefit / cost ratio
Existing tunnel	-	-	-
Alternative 2	1.5769	7.055	0.22
Alternative 3	1.5797	9.097	0.17
Alternative 5	1.8280	9.495	0.19

Table 7.4 Total safety benefits per year using marginal costs and the costs of the Alternatives 2, 3 and 5 converted into annual costs using an annuity factor and inflation factor (based on interest rate 5% and inflation 1%).

As an investment in safety the three alternatives do not have a benefit safety ratio over 1. The values of the ratios between safety benefit and costs are in the magnitude 0.2. The low value of benefit/cost is partly a result of the rather high interest rate of 5%. If a lower value of the interest rate is used, say, 2%, then the benefit/cost ration would be approximately 0.3 – 0.35, which is still significantly below 1.

It can also be investigated, whether the larger total safety benefits of Alternative 5 compared to Alternative 2 would have a benefit/cost ratio when considering the higher annual total costs as shown in Table 7.5.

	Total safety benefits /year using marginal costs [MEUR/year]	Annual total costs for construction and refurbishment [MEUR/year]	Safety benefit / cost ratio
Alternative 2	-	-	-
Alternative 5	0.2511	2.440	0.10

Table 7.5 Total safety benefits per year of Alternative 5 relative to Alternative 2 using marginal costs and the investments converted into annual costs using an annuity factor and inflation factor (basis: interest rate 5%, inflation 1%).

Regarded as an investment in safety alone, the three alternatives do not seem to be cost efficient. However, considering the upper limit of the fatality rate, the existing situation is not acceptable and improvements must be made (see Figure 7.1 and the explanation of the risk acceptance criteria in section 3.1). The most cost efficient solution with respect to safety is Alternative 2. Alternative 5 brings further safety improvements and the benefit/safety ratio is only slightly lower than the ratio for Alternative 2. However, relative to the additional costs the benefit/cost ratio does not justify Alternative 5.

Evaluation of alternatives including socio-economic costs of detours

In the following the benefits and costs are evaluated when also the socio-economic benefits of the traffic reduction is taken into account. The safety related benefits stated in Table 7.4 and the traffic related improvements from Table 6.6 are combined in Table 7.6.

	Traffic benefits/year [MEUR/year]	Total safety benefits /year using marginal costs	Combined benefits/year [MEUR/year]	Annual total costs for construction and refurbishment [MEUR/year]	Combined benefit / cost ratio
Existing tunnel	-	-	-	-	-
Alternative 2	0	1.5769	1.5769	7.055	0.22
Alternative 3	-4.023	1.5797	-2.4433	9.097	-0.26
Alternative 5	9.496	1.8280	11.3236	9.495	1.19

Table 7.6 Socio-economic benefits for traffic and total safety benefits in terms of MEUR/year as well as the costs of the Alternatives 2, 3 and 5 converted into annual costs using an annuity factor and inflation factor (basis: interest rate 5%, inflation 1%).

As it appears from Table 7.6, the benefit of the reduced traffic becomes a decisive part of the comparison: Alternative 5 has a combined benefit/cost ratio over 1.00 and can based on this evaluation be recommended. Alternative 2 is unaffected by the traffic benefits and the combined benefit cost ratio remains 0.22. For Alternative 3 the combined benefit cost ratio is below 0, which implies that the traffic disadvantages are more important than the safety improvements.

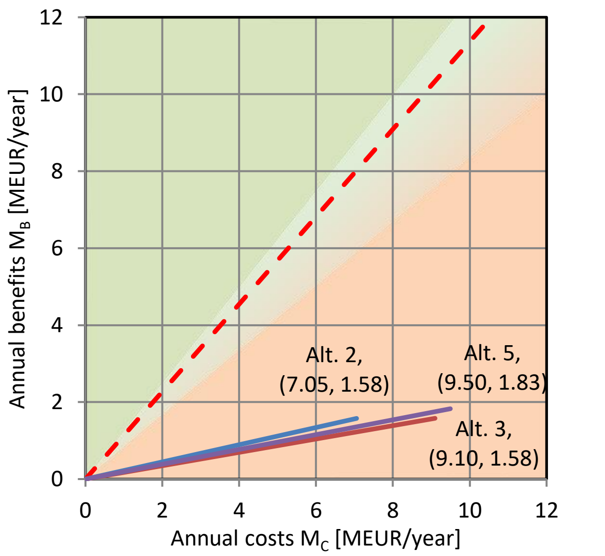


Figure 7.2 Total safety benefits per year using marginal costs and the costs of the Alternatives 2, 3 and 5 converted into annual costs

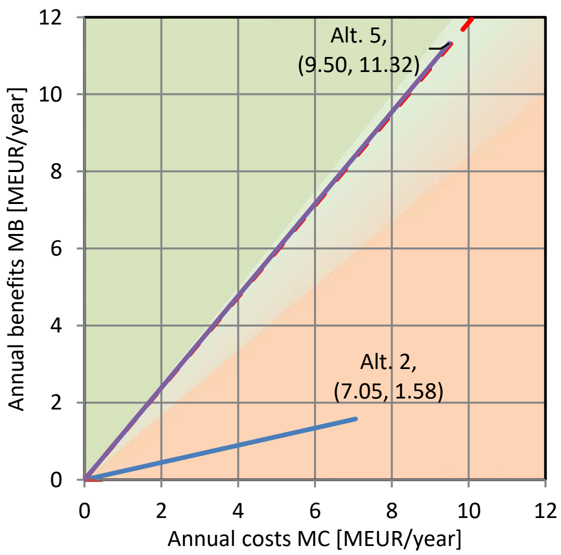


Figure 7.3 Socio-economic benefits for traffic and total safety benefits as well as the costs of the Alternatives 2 and 5 converted into annual costs.

As mentioned above, the interest rate of 5% used in the annuity calculations is unusually high. With an interest rate of 2%, the combined benefit/cost ratios for Alternatives 2, 3 and 5 would be 0.36, -0.44 and 1.94, respectively.

If the socio-economic costs per vehicle-km would be halved to 0.45 EUR/km, (with interest rate = 5%) then the combined benefit/cost ratios for Alternatives 2, 3 and 5 would be 0.22, -0.05 and 0.69, respectively. (With interest rate = 2%, the combined benefit/cost ratios would be 0.36, -0.08 and 1.13, respectively).

If the injury and fatality rate on the open roads outside the tunnel would be reduced with 50% (possibly as effect of safety measures), the safety-related differences between the alternatives would be reduced, however, because the effect of the traffic-related benefits is dominating, the effect is marginal: The combined benefit/cost ratios for Alternatives 2, 3 and 5 would be 0.22, -0.26 and 1.16, respectively.

The crude sensitivity analysis illustrate that Alternative 5 consistently is the most favourable solution, when the combined socio-economic costs of traffic and safety is considered. The benefit/cost ratio is over 1.00, unless the socio-economic costs per vehicle-km is significantly lower than assumed in the present report. In any case, considering the upper limit of the fatality rate, the existing situation is not acceptable and improvements must be made (see Figure 7.1 and the ex-planation of the risk acceptance criteria in section 3.1) and the most cost efficient solution with respect to combined socio-economic costs is consistently Alternative 5.

Alternative 2 or Alternative 5
The existing tunnel will not be acceptable for the projected future traffic across Hvalfjörður. Furthermore, it can be concluded from the comparisons above that Alternative 3 does not appear preferable in any of the comparisons. Only the fatality rate per billion veh-km of Alternative 3 is slightly below the fatality rate of Alternative 2. The annual number of fatalities is higher for Alternative 3 than for Alternative 2, so the slightly reduced fatality rate is not a real benefit. Alternatives 1 and 4 lie between Alternative 2 and 3 and are also not considered further.

The remaining possible solutions are Alternative 2 and Alternative 5.

Considering tunnel safety alone, Alternative 2 will have the lowest expected number of fatalities in the tunnel. The expected number of accidents, injuries and fatalities inside the tunnels in Alternative 5 is significantly higher. However, when also the accidents on the roads outside the tunnel are taken into account the number of fatalities in the two alternatives are closer, but still Alternative 2 is expected to have the lowest number of fatalities in the tunnel and on the open roads combined. On the other hand, the combined number of injuries in the tunnel and on the open roads will be lower for Alternative 5 than for Alternative 2. Using weight factors (marginal costs) for fatalities and injuries, the comparison of the combined safety in terms of fatalities and injuries for the tunnel and the open roads demonstrates that Alternative 5 has an overall better safety performance than Alternative 2.

Even though the safety performance is generally better for Alternative 5 than for Alternative 2, it should be considered that the traffic going to Akranes (35%

of the traffic) will by far have a less preferable solution with Alternative 5. For them the risk in Alternative 5 is higher than in Alternative 2 and they will have no benefits with respect to traffic.

The better overall safety performance of Alternative 5 comes with higher construction costs. In comparison, regarding safety issues only, the benefit/cost ratio for establishing Alternative 2 is preferable to Alternative 5.

Taking into account also the socio-economic benefits related to the traffic, Alternative 5 comes out significantly more favourable than Alternative 2. Considering the socio-economic costs of traffic, fatalities and injuries for the tunnels and the open roads around the tunnel, Alternative 5 has a benefit/cost ratio over 1.00 and in sensitivity analyses it is consistently preferable to Alternative 2.

Compliance

The maximum gradient of both tubes in Alternative 2 are over 8% and thereby over the limit of 5% described by the EU directive and the Norwegian standard HB N500. However, the limits are valid for new tunnels only and if the extension of the existing Hvalfjörður tunnel in Alternative 2 is regarded rather an improvement of a tunnel than a new tunnel, then the gradient may be regarded not to violate the guidelines. Alternative 2 has exits and cross passages for each 500 m, which is in compliance with the EU directive but not in compliance with the Norwegian HB N500, which requires cross passages for each 250 m for tunnels with two tubes.

It must be further discussed and decided whether the adherence to the Norwegian standard is mandatory in this case. Apart from this, the improvement of the tunnel seems to be compliant with the regulation.

Alternative 5 may have to be regarded as two tunnels: The Western tube is thereby an improvement of the existing Hvalfjörður tunnel and the Eastern tube is a new tunnel. The improvement of the existing tunnel tube and the reduction of the traffic in that tube does not violate any regulations. The Eastern tube regarded as a new tunnel is compliant to the EU Directive 2004/54/EC and the Norwegian standard HB N500 with respect to the gradient (which is maximum 5.0%). However, according to the Norwegian HB N500, a tunnel with a length of 7.5 km and an AADT of 15000 should be built with two tubes and unidirectional traffic and should have exits through cross passages for each 250 m. Hence, the tunnel figuration does not respect the guidelines, the distances are too long (according to the Norwegian standard) and half of the exits are connected to emergency rooms, which formally do not live up to the requirements given in the EU directive and in the Norwegian standard.

It may be argued that the emergency rooms are sufficiently safe and that they provide the same functionality for the tunnel users as the cross passages do. It might also be claimed that the risk analyses indicate that the distance of 500 m is sufficient (even though this point has not been specifically investigated), and finally it is evident that the risk reduction by establishing two tubes for the Eastern tunnel will not be cost efficient in relation to the risk reduction. (This solution would increase the construction costs by approximately 110 – 150 MEUR, resulting in annuity costs of 7 – 9 MEUR and the risk reduction would be reduced with a capitalised value of approximately 0.3 MEUR). Nevertheless, Alternative 5 does not seem to be compliant with the regulation used for tunnels in Iceland, the Nordic countries and Europe in general.

7.2 Summary and conclusion

The risk estimation shows that the risk in the tunnel as it is today with the traffic prevailing in ~2040 is higher than the upper limit and thereby inacceptable.

Five alternatives have been studies. For three of them detailed quantified risk analyses have been carried out, and the risk has been assessed and evaluated. The conclusion is that two alternatives may be considered possible candidates for an improvement of the Hvalfjörður tunnel: either an adjacent tunnel tube similar to the existing tunnel with cross passages between the two tunnels (Alternative 2), or a new tunnel with an alignment pointing in the direction of Highway No. 1 (Alternative 5).

Alternative 5, which involves a new longer tunnel for Highway No. 1 is the most preferable from a socio-economic point of view. The dominating contribution to this conclusion is the reduced driving costs for the traffic along Highway No. 1 and the reduction of traffic accidents on the open roads.

For the traffic to and from Akranes, Alternative 5 is less preferable than Alternative 2, because the fatality risk in the existing tunnel tube remains relatively high, and the reduced driving costs do not affect this part of the traffic. Furthermore, the solution in Alternative 5 is not in conjunction with the regulation with respect to tunnel configuration, traffic mode and means of evacuation.

It must be further considered if it is acceptable not to be in compliance with the guidelines on these points.

Answer to the questions

Answers to the five questions given in the objectives of the risk analysis, section 1.2, can be answered based on the investigations:

a) Is better to drive up or down on the 8% gradient on the north side?	In Table 5.3 and Table 5.4 the summary of results for unidirectional traffic in the existing tunnel tube is shown. In Table 5.3 the traffic is Northbound, in Table 5.4 the traffic is southbound. The traffic volume is the same in the two cases. As expected, the number of accidents, and injuries and fatalities from accidents is approximately the same in the two cases. For fires, however, a significant difference can be noticed. The steep upwards gradient result in an increased number of fires, approximately 30% more fires are expected. On the other hand, the fires on a downwards part of a tunnel with unidirectional traffic may result in more severe consequences, because the smoke going up may flow over stopped vehicles. The expected number of fatalities is increased with about 30% in spite of the reduced number of fires. In totality, the fatality rate is only modestly increased for the Southbound traffic going downwards on the steep part of the tunnel, but the conclusion may be that it is slightly better to use the existing tunnel tube for Northbound traffic.

b) One-directional tunnel has advantages which could be highlighted in the comparison, i.e. overtaking is possible almost without risk, no traffic jam behind heavy vehicles, and in case of fire, smoke can be blown away from tunnel users which is not the case in bi-directional tunnels.	The advantages of unidirectional traffic in the tunnel tubes is an integrated part of the risk estimation: The number of accidents are reduced compared to the similar traffic in tunnel tubes with bidirectional traffic and the consequences of the accidents and fires are reduced as well. The result of this can be noticed in the lower fatality rate in Alternatives 2 and 3 compared to Alternative 5. In Alternative 2 and 3 the rates in the existing tunnel tube are 2.99 fatalities per billion veh-km and 2.60 fatalities per billion veh-km, respectively. The difference is owing to the direction as discussed in point a). In Alternative 5 the rate is 7.28 fatalities per billion veh-km, in spite of the lower traffic, which tend to reduce the fatality rate. The advantages in terms of traffic flow, owing to the possibility of overtaking slow vehicles has not been dealt with specifically. The quantification of depends on the share of slow vehicles, the probability of the remaining traffic of being delayed by slow traffic and the estimate of the delay and finally the weight factor for the delay. The value would be part of the socio-economic evaluation, it would benefit Alternative 2 and 3 over Alternative 5, and as it can be seen in Table 7.6, the difference between Alternative 5 and the second-best Alternative 2 is approximately 10 MEUR/year in socioeconomic value per year. The advantage of overtaking will not change this ranking.
c) For route 5, maintenance and repair can be more easily accomplished as one tunnel can be closed at night time and traffic directed to the other tunnel in meanwhile. For the other alternative routes special measures are needed to change each of the tunnel tubes into bi-directional tunnels with necessary signals and extra costs, probably also increased risk.	The question of closing a tunnel tube for maintenance, repair etc. has been discussed in section 6.2. It is correct that one tube can be more easily closed in Alternative 5, but it is recommended in section 6.2 that the tunnel tubes should be prepared for bi-directional traffic also in the other alternatives. The preparation for bi-directional traffic seems to be cost efficient. If the alternative to bi-directional traffic is a detour around the fjord, the risk will most likely not be increased. In any case, a good warning about the unusual situation should be prepared.
d) Emergency rooms without exit to the open is not accepted by the European regulation, but Norwegians aim at getting an approval for this.	It is correct that emergency rooms without exit to the open are not accepted by the European regulation – and also not accepted in the current Norwegian standards. For existing tunnels it can be claimed that emergency rooms are better than nothing, and it may be argued that the emergency rooms are sufficiently safe and that they provide the same functionality for the tunnel users as the cross passages do. Whether it is acceptable to plan a new tunnel with emergency rooms is one of the open questions, as discussed in the end of section 7.1.
e) Would it be better to have a wider tunnel cross section for the first 300 to 500 m such that barrier can be placed between the opposite driving lanes?	The first 300 m – 500 m has an increased frequency of accidents (see Figure 5.3, Figure 5.4, Figure 5.11, Figure 5.12, Figure 5.19 and Figure 5.20), and a good division of the traffic directions for bi-directional traffic (i.e. in Alternative 5) may be an advantage. On the other hand care should be taken not to establish an object which is prone to collision, in which case the barrier could be counter-productive. In addition it should be possible to pass a broken-down vehicle and emergency vehicles should have sufficient space to enter the tunnel. It might be an option to establish a slightly elevated central reserve, lights and rumble stipes in the portal area in order to ensure the partition of the driving directions.

8 References

Project specific references

[1] Hvalfjörður Road Tunnel, Contribution to Risk Analysis, Mannvit/ Spölur, HOJ, April 2013, Revised Nov. 2017.
[2] Drawing Mannvit for Spölur: Hvalfjarðargöng, Örtggi I Jardgömgum, Yfirtskort Langsnid, Veg nr. 1, Utgafa: 01. 1.020.228, Nov 2012.
[3] Vegargerðin Hvalfjarðargöng, Umferðarúttekt – Umferðarspá, Mars 2006
[4] Hvalfjarðargöng, Úttekt á aðlögunarlýsingu, Mannvit Nóv 2012
[5] Accident rate Hvalfjord tunnel and roads in Iceland (Excel sheet provided by Vegagerðin, 2019)
[6] Copy of General information table (Excel sheet provided by Vegagerðin, 2019)
[7] Copy of Traffic updated (Excel sheet provided by Vegagerðin, 2019)
[8] Tvöföldun Hvalfjarðarganga. Samanburður mismunandi gangaleiða. Greinargerð, Mannvit, Vegagerðin 17. april 2018, (translated into English: October 2019)
[9] Hvalfjarðargöng II Gangaleiðir plan og snið_Teikn 1 ril 6 feb. 2018, Mannvit, Vegagerðin February 2018.
[10] Memo on risk calculation procedures in Hvalfjord Tunnel, Mannvit 27.10.2019
[11] Memorandum Hvalfjord subsea tunnel II. Comparison of alternatives. Oct. 2019 (Translation of report from April 2018: Greinargerð. Tvöföldun Hvalfjardðarganga. Samanburður mismunandi gangaleiða)

Other Icelandic references

[12] Memo: Review and comments to shelters after visit to Norðfjarðargöng, 25. April 2019 HOJ Consulting to Vegagerðin.

International references

[13] Directive 2004/54/EC of the European Parliament and of the Council on Minimum Safety Requirements for Tunnels in the Trans-European Road Network. The European Union, The European Parliament, The Council, Brussels, 29 April 2004
[14] Håndbok N500 HB N500 Vegtunneler, Statens vegvesen, 2016.
[15] UNECE, UNITED NATIONS, Economic and Social Council Distr. GENERAL TRANS/AC.7/9, 10 December 2001, ECONOMIC COMMISSION FOR EUROPE, INLAND TRANSPORT COMMITTEE, Ad hoc Multidisciplinary Group of Experts on Safety in Tunnels, RECOMMENDATIONS OF THE GROUP OF EXPERTS ON SAFETY IN ROAD TUNNELS FINAL REPORT
[16] PIARC World Road Association PIARC committee on Road Tunnels (C5), Fire and Smoke Control in Road Tunnels, 1999.
[17] OECD/IRTAD International Road Traffic and Accident Database.
[18] CARE Community Road Accident Database. EU Directorate-General for Energy and Transport. Web-based database http://europa.eu.int/comm./transport/care
[19] OECD. Safety in Tunnels. Transport of Dangerous Goods through Road tunnels. OECD, PIARC, Paris 2001.
[20] Development of a best practice methodology for risk assessment in road tunnels. Utvikling av beste praksis metode for risk modeling for vegtunneler. Matrisk GmbH and HOJ Consulting GmbH. Research project ASTRA 2009/001 at request of Federal Road Office (FEDRO) and Norwegian Public Roads Administration (NPRA), November 2011.
[21] Moderne Vegtunneler" research programme: "Utvikling av risikoanalysemodell TRANSIT for Vegtunneler", Statens vegvesens rapporter Nr. 156, Aug 2012.
[22] ASTRA 19004 Richtlinie ASTRA 19004 Risikoanalyse für Tunnel der Nationalstrassen Ausgabe 2014 V1.10. Bundesamt für Strassen (Guideline risk analysis of tunnels on the national roads): , (Federal Roads Office, Switzerland, 21.2.2019)
[23] ASTRA 89005 Dokumentation Risikokonzept für Tunnel der Nationalstrassen Methodik zur Ermittlung und Bewertung der Risiken in Tunneln Ausgabe 2014 V1.10 ASTRA 89005 Bundesamt für Strassen (Documentation, Methodology for Assess-

ment and Evaluation of Risks in Tunnels), (Federal Roads Office, Switzerland, 21.2.2019).

[24] HB V712 Håndbok V712 Konsekvensanalyser, Statens vegvesen, Vegdirektoratet, Norge, 2018.

[25] NordFoU: "Evakuering i vegtunneler" DP3 Obj. Nr. 2011/052970-016, Pr. nr. 10.11004.01.01, Rapp. nr. 11-004-04, Ver. 1.3, 2015-08-20.

9 Appendix: Traffic prognosis

AADT Annual Average Daily Traffic

The traffic registrations has been provided by Vegargerðin based on Information from the road toll collection on monthly traffic distribution in Hvalfjorður tunnel: The traffic development from 1999 – 2019 is shown in Table 9.1 in terms of AADT, SDT and WDT.

Year	AADT	SDT	WDT	Comment
1999	2938	4013	2013	
2000	3241	4438	2207	
2001	3557	4770	2632	
2002	3660	4866	2728	
2003	3846	5132	2809	
2004	4103	5376	2985	
2005	4715	6077	3632	
2006	5066	6455	4065	
2007	5579	7066	4280	
2008	5420	6826	4384	
2009	5421	6950	4237	
2010	5377	6906	4224	
2011	5070	6729	3809	
2012	5007	6601	3780	
2013	5149	6655	4067	
2014	5306	6974	3979	
2015	5637	7475	4115	
2016	6404	8310	4899	
2017	6981	8939	5'425	
2018	7266	9109	5736	
2019	7850	9800	5960	Preliminary estimate

Table 9.1 Traffic registration in the years 1999 – 2019 (Traffic for 2019 are)

For the studies in the present report, an AADT of 15000 veh/d has been given as the assumption. This value is fitting well with an annual increase of traffic of 3.13% per year as it is illustrated in Figure 9.1.

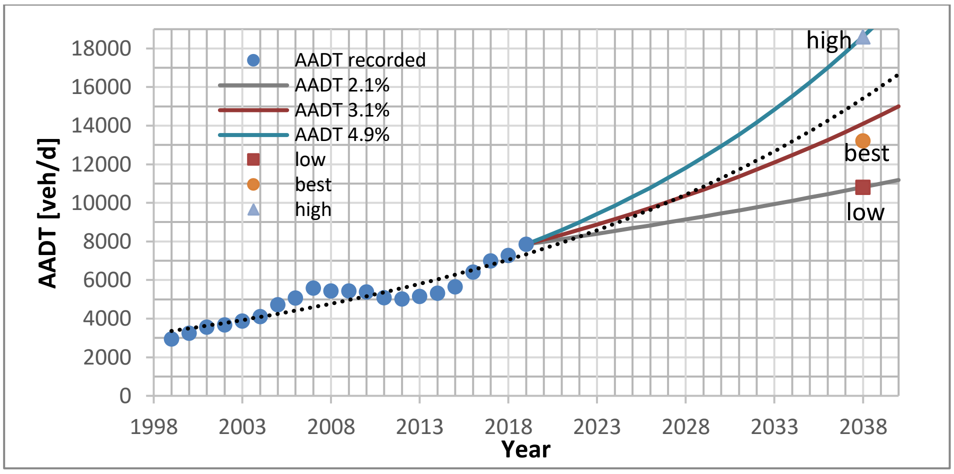


Figure 9.1 Recorded AADT and forecasts to 2040

HGV percentage

For the studies in the present report, an HGV percentage of 8% has been given as the assumption

10 Appendix: The existing Hvalfjorður Tunnel

10.1 Tunnel description

The existing tunnel is located North of Reykjavík as part of Highway No. 1. Characteristics of the existing tunnel has been identified and discussed in the risk analyses from 2013 (updated in 2017) [1]. For reference the existing tunnel is studied in this chapter with the traffic corresponding to the extension alternatives. The alignment, longitudinal profile and cross sections are illustrated in Figure 4.1, Figure 4.2 and Figure 4.3.

10.1.1 Key facts about the existing tunnel

- The tunnel was designed in accordance with the Norwegian road tunnel standards from the 1990'ies and opened for traffic in July 1998.
- 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
- Rock support is mainly rock bolts and sprayed concrete.
- Water leakage (total) < 5 l/s. Water shielding to ensure no dripping on the road.
- Pumping gallery with 3 high thrust pumps and storage chamber for 7500 m^3
- Four transformer stations in tunnel, all concrete buildings

10.1.2 Existing tunnel, general information

Geometry	
Length of tunnel	5.770 km
Max slope	8.1%
Tunnel cross section	T8.5 (2 lane) and T11 (3 lane on 2 km with 8.1%)
Lane width (m)	3.25
Walkways	Yes , 0.75 m each side 5% sideslope
Concrete wall barrier (Føringskant)	No
Minimum horizontal radius	R = 350 m
Traffic	
Traffic AADT 2018	7266 veh/day (2x3633)
Traffic AADT ~2040 for comparison	15000 veh/day (two directions: 2x7500)
HGV %	8%
Transport of dangerous goods	0.065%
Speed limit	70 km/h
Traffic jams	No
Bidirectional traffic	Yes
Ventilation	
Ventilation	Longitudinal
Design fire	50 MW
Minimum air speed provided	3 m/s
Number of fans	32 reversible
Fire ventilation	Yes
Minimum thrust force	21000 N
Impeller diameter of fan	1000 mm
Nominal thrust per fan	735 N
Air flow measurement device	In the middle of tunnel
NO/CO measurement device	Every 1500 m
Smoke detection	No, only CO sensor and dust sensor

Safety and management systems	
Rumble strips	Rumble strips on centreline only
Drainage system	Yes, gutter c/c 80 m
Luminance	2 cd/m^2 day; 1 cd/m^2 night
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-bys	Every 500 m
Turning bays	Every 1500 m designed for large vehicles
Blinking light and sign at turning bay	Every 1500 m
Speed supervision	Yes
Markings showing distance to portals	Every 1000 m
Markings showing speed limit	In the tunnel and outside the tunnel
Speed camera for ticketing	Inside the tunnel
Traffic surveillance	Cameras at portals + in the tunnel (incident detection)
Automatic incident detection	Yes
Red lights to indicate tunnel closure	At both portals
Physical barrier to stop traffic.	At both portals
Road temperature measurement device	2 devices, at both portals
Air temperature measurement device	3 devices, at both portals and close to middle
Humidity measurement device	3 devices, at both portals and close to middle
Communications	Tetra and GSM
Radio interruption	Yes
Control centre	Yes, 24 h
Oil seperator	Outside of tunnel where water is discharged

Table 10.1 Information about the design and equipment in the Hvalfjörður Tunnel.

10.1.1 Cross sections

With the width of 3.00 - 3.25 m the lanes are relatively narrow. Walkways are located on each side with 0.75 m width and 5% side slope. The tunnel walls are uneven and rough in surface, resulting from the construction process. The tunnel wall is not lined with a concrete barrier (Føringskant).

10.1.2 Lay-bys

Emergency lay-bys are located every 500 m, and turning bays designed for large vehicles every 1500 m. The lay-bys are located at the following locations:

Chainage		Type	Side	Distances: Lay-bys (m)	
				L	R
1	2100	SP	L		510
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	
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

Legend: L: left; R: right,
Type SP, SN and N, SN*:
Two-lane turning bay

Table 10.2 Location and distance between lay-bys..

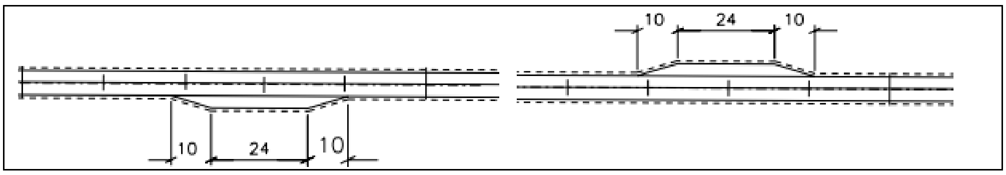
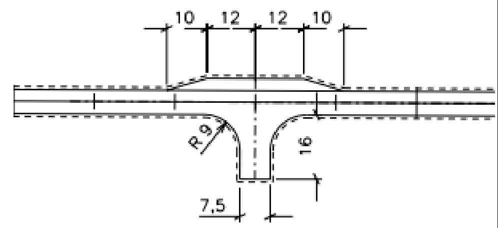


Figure 10.1 Lay-by type N right and left position (unit: m).



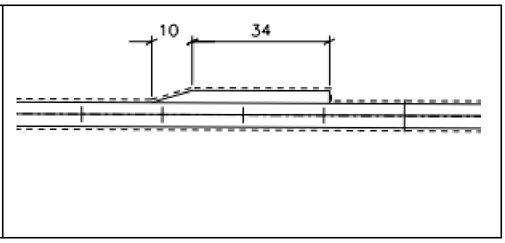


Figure 10.2 Lay-by, turning bay type SN. *Figure 10.3 Lay-by type SP (unit: m).*

10.1.1 Tunnel sections

The alignment the tunnels is modelled by dividing the tunnel into 18 sections.

North bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
H1n	S Portal	1590	50	316	-5.28	1	3.25	7500
H2n		1640	50	632	-5.28	1	3.25	7500
H3n		1690	100	635	-7.00	1	3.25	7500
H4n		1790	245	635	-7.00	1	3.25	7500
H5n		2035	415	400	-7.00	1	3.25	7500
H6n		2450	371	∞	-7.00	1	3.25	7500
H7n		2821	2168	∞	-4.43	1	3.25	7500
H8n		4989	66	∞	0	1	3.25	7500
H9n		5055	220	470	0	1	3.25	7500
H10n		5275	147	∞	8.09	2	3.00	7500
H11n		5422	178	∞	8.09	2	3.00	7500
H12n		5600	495	488	8.09	2	3.00	7500
H13n		6095	305	∞	8.09	2	3.00	7500
H14n		6400	605	488	8.09	2	3.00	7500
H15n		7005	255	∞	8.09	2	3.00	7500
H16n		7260	100	∞	8.09	2	3.00	7500
H17n		7360	50	∞	8.09	2	3.00	7500
H18n	N Portal	7410	50	∞	3.89	2	3.00	7500

South bound	Type of section	Chainage	L (m)	H- radius (m)	Gradient %	Lanes	Lane width (m)	AADT* veh/day
H1s	N Portal	7460	50	∞	-3.89	1	3.00	7500
H2s		7410	50	∞	-8.09	1	3.00	7500
H3s		7360	100	∞	-8.09	1	3.00	7500
H4s		7260	255	∞	-8.09	1	3.00	7500
H5s		7005	605	488	-8.09	1	3.00	7500
H6s		6400	305	∞	-8.09	1	3.00	7500
H7s		6095	495	488	-8.09	1	3.00	7500
H8s		5600	178	∞	-8.09	1	3.00	7500
H9s		5422	147	∞	-8.09	1	3.00	7500
H10s		5275	220	470	0	1	3.25	7500
H11s		5055	66	∞	0	1	3.25	7500
H12s		4989	2168	∞	4.43	1	3.25	7500
H13s		2821	371	∞	7.00	1	3.25	7500
H14s		2450	415	400	7.00	1	3.25	7500
H15s		2035	245	635	7.00	1	3.25	7500
H16s		1790	100	635	7.00	1	3.25	7500
H17s		1690	50	632	5.28	1	3.25	7500
H18s	S Portal	1640	50	316	5.28	1	3.25	7500

Table 10.3 Tunnel geometry and traffic. The tunnel is divided into 18 sections in each direction. AADT is for the year ~2040 covering each direction in the hypothetical case of no extension of the tunnel system.

10.1.2 Ventilation

32 reversible 1000 mm fans each with a thrust of 735 N, minimum thrust force 21 kN. For a 50 MW fire an air speed of 3 m/s can be provided. For a 20 MW fire 3.5 m/s can be provided.

10.1.3 Lighting

The luminance in the existing tunnel has been measured [4] in order to control the compliance with the regulation ([14]). A luminance of 2 cd/m^2 in the interior of the tunnel was documented, which is sufficient for AADT less than 8000 veh/d. For AADT over 8000 veh/d the luminance shall be minimum 4 cd/m^2.

The measurements of the luminance in the portal areas are illustrated in Figure 10.4. It is demonstrated that the luminance is slightly below the requirements In the first 50 m, whereas the luminance appears to be over the requirements for the remaining part.

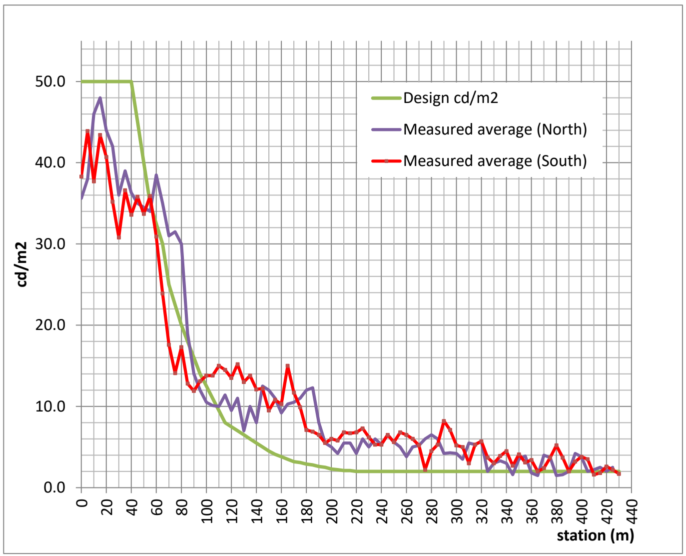


Figure 10.4 Lighting in Hvalfjörður Tunnel at North and South portal. Comparison of measurements with requirements (ref. HB N500 [14])

10.2 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 [20], [21] and as part of the Swiss Guideline [23]. Generally the Transit version with Norwegian data is used, but the use of the program has been adapted to Icelandic conditions. When emergency exits are significantly over 1000 m, the improved ventilation and evacuation model from the Swiss version, which has been used for the alternatives, cannot be applied.

10.2.1 Accidents, Fires and Dangerous Goods Events

The risk in the hypothetical case of no extension of the tunnel system will be determined for comparison. Characteristics of the existing tunnel has been identified and discussed in the risk analyses from 2013 (updated in 2017) [1]. However, the present analysis is updated with respect to traffic, ventilation and modelling of the monitoring system.

The ventilation system of the existing tunnel has 32 fans, which is not compliant with the with the requirement. The upgraded existing tunnel in the Alternatives 1- 5 include additional 8 fans. The compliance of the longitudinal ventilation of the existing tunnel is based on the available thrust compared to the required thrust 32/40 = 80%. A aggregated resulted with weighted calculations with longitudinal and natural ventilation with factors 0.8 and 0.2 are shown in Table 10.5.

In addition to the tunnel characteristics directly included in the models of the analysis tool, the modifications in Table 10.4 have been taken into account.

Characteristic	Modification
Rough walls	Modification by increase factor of 1.15 on frequency of injury accidents
Ventilation system	Modification by increase factor of 1.4 on consequence of fires
Banning of DG from rush hours.	Risk is reduced to 20% of the value calculated for a tunnel without restrictions

Table 10.4 Existing tunnel: Modifications to Transit calculations

The summary of the results is shown in Table 10.5 and in Figure 10.7 - Figure 10.6, which are illustrating the profile of accidents and fatalities along the tunnel alignment.

Hvalfjörður Tunnel, Existing tunnel, ~2040				
	Number killed / year	Number injured /year	Number events /year	
Accidents	0.3959	10.167	7.073	
Fires	0.0262	0.226	2.563	
Dangerous goods	0.0000	0.000	0.000	
Total	0.4221	10.394	9.637	
Traffic	32.14		Mill. veh-km/yr	
Accident rate	0.220		Per Mill. veh-km	
Fire rate	0.080		Per Mill. veh-km	
Fatality rate	13.13		Per Bill. veh-km	

Table 10.5 Existing tunnel: Summary of estimated risk for ~2040 (speed limit 70 km/t).

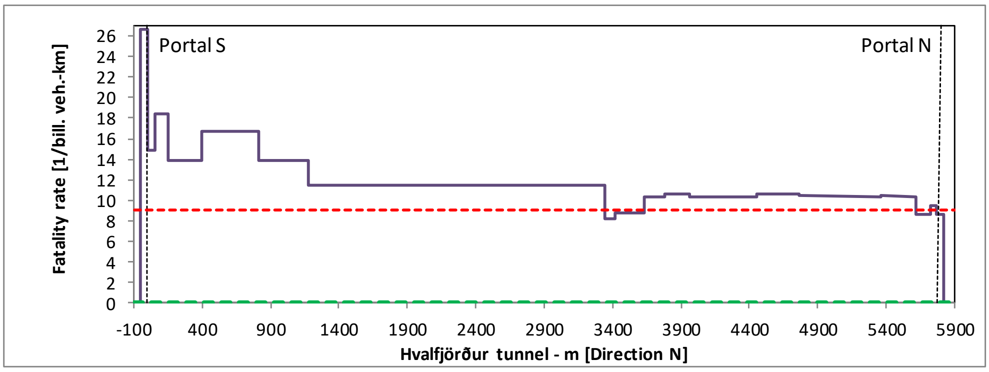


Figure 10.5 Existing tunnel: Northbound direction: Fatality rate per segment and million vehicle km ~2040. North is to the right at the first axis.

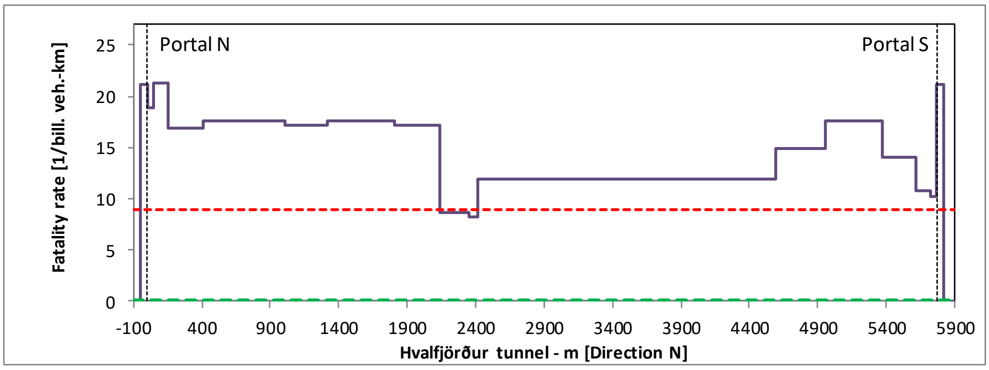


Figure 10.6 Existing tunnel: Southbound direction: Fatality rate per segment and million vehicle km ~2040. South is to the right at the first axis.

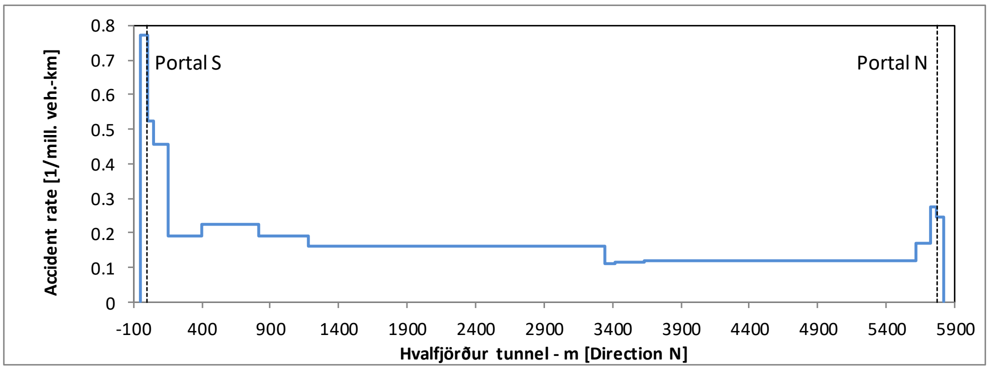


Figure 10.7 *Existing tunnel: Northbound direction: Accident rate per segment and million vehicle km ~2040. North is to the right at the first axis.*

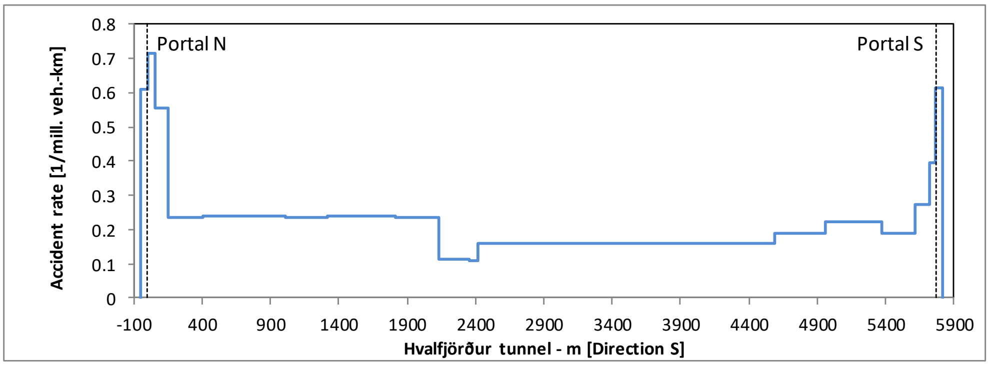


Figure 10.8 *Existing tunnel: Southbound direction: Accident rate per segment and million vehicle km ~2040. South is to the right at the first axis.*

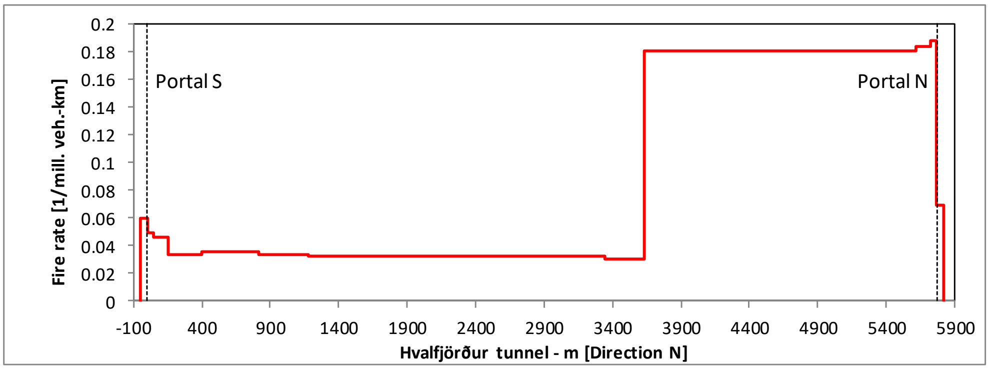


Figure 10.9 *Existing tunnel: Northbound direction: Fire rate per segment and million vehicle km ~2040. North is to the right at the first axis.*

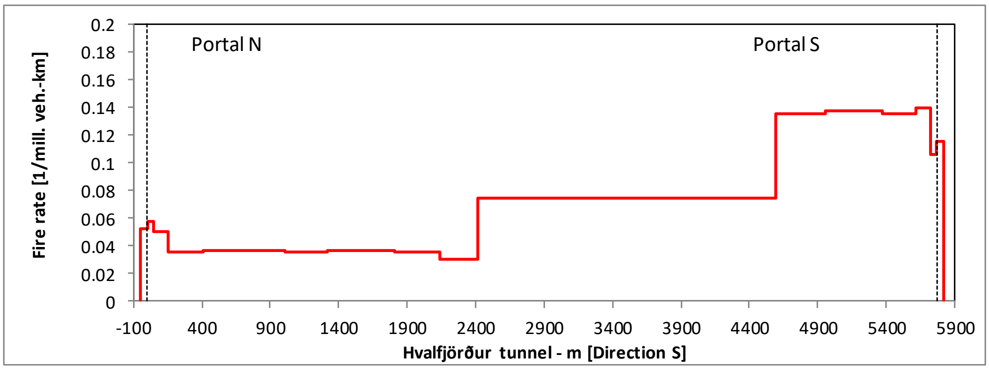


Figure 10.10 *Existing tunnel: Southbound direction: Fire rate per segment and million vehicle km ~2040. South is to the right at the first axis.*

The graphical illustrations illustrate the influence of the tunnel characteristics. The influence of the portals, the gradients and the curvature is evident.

The summary reveals that the fatality rate is higher than the upper limit and significantly increased compared to the estimates in the risk analysis of 2013/2017 [1]. The main reason for the increase is the assumption of AADT is higher than the "high" traffic estimate in the 2013/2017 analysis.

The speed limit of 70 km/h 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 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.