

no. 98

Publication

Subsea road tunnels in Norway



**Norwegian Public Roads
Administration**

Road Technology Department

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Front cover design: Svein Aarseth, Oslo
Layout: OPTIMAL AS, Oslo
Editing/production co-ordinator: Helge Holte
Printed by: OPTIMAL AS, Oslo
Edition: 1000

Harald Buvik has assisted in the editing of the publication.

Preface

The first Norwegian subsea tunnel was opened in 1983. Subsequently 21 other subsea tunnels have been built. As a result, in the summer of 2001 a total of 22 tunnels with a total length of almost 90 km are open to traffic. Yet another tunnel, Skatestraumen tunnel, will soon be completed. Several other subsea tunnels are also in the process of being planned, including tunnels of up to ten kilometres length.

Experiences from these tunnels are the theme for this article. Generally speaking, building costs for subsea tunnels have been reduced over the years. However, costs vary a great deal from project to project. Operation and maintenance costs also vary considerably. Costs for reinvestment and equipment are particularly high. Water ingress has diminished over time, so that the need for pumping leakage water has been reduced.

This study of accidents and fires in Norwegian subsea tunnels covers 17 tunnels opened before 1996. 19 personal injury accidents covering the five years from 1995 including 1999 were analysed. The accident rate was as low as 0.09 (injury accidents per mill vehicle kilometre per year). The rate was highest in tunnels with steep gradients and where AADT was lower than 1500. Only three fires have been recorded in Norwegian subsea tunnels. This amounts to a rate less than 10% of the accident rate. As the study covers only 17 tunnels and 19 accidents, the results must be interpreted with this in mind.

*Norwegian Public Roads Administration
Oslo, September 2002*

1 Development



Until the end of the seventies, numerous large bridges were built over Norwegian fjords, or between some of the many islands along the coast. As the bridge span lengths increased, so did the costs, and alternative methods of crossing, such as pontoon bridges, immersed-tube tunnels and subsea rock tunnels, were considered.

The first Norwegian subsea road tunnel was built at Vardø, Norway's most easterly town, between 1979 and 1983. After the Vardø tunnel was opened, 21 others have been built and opened to traffic. Another one is under construction, this is Skatestraumen in Sogn og Fjordane, whilst the plans for Eiksund tunnel have been finalized. When the Eiksund tunnel has been opened in a few years time, there will be about one hundred kilometres of subsea road tunnels in Norway.

Most of the tunnels have two lanes, but some tunnels have an extra lane where there are steep gradients. The Tromsø Sund tunnel is built in two tubes, so that the tunnel has in reality 4 lanes throughout its entire length. The two tunnels, Valderøy and Ellingsøy were built simultaneously in one operation. In several of the tables which are shown in this article, data from these two tunnels are combined under the name «the Ålesund tunnels».

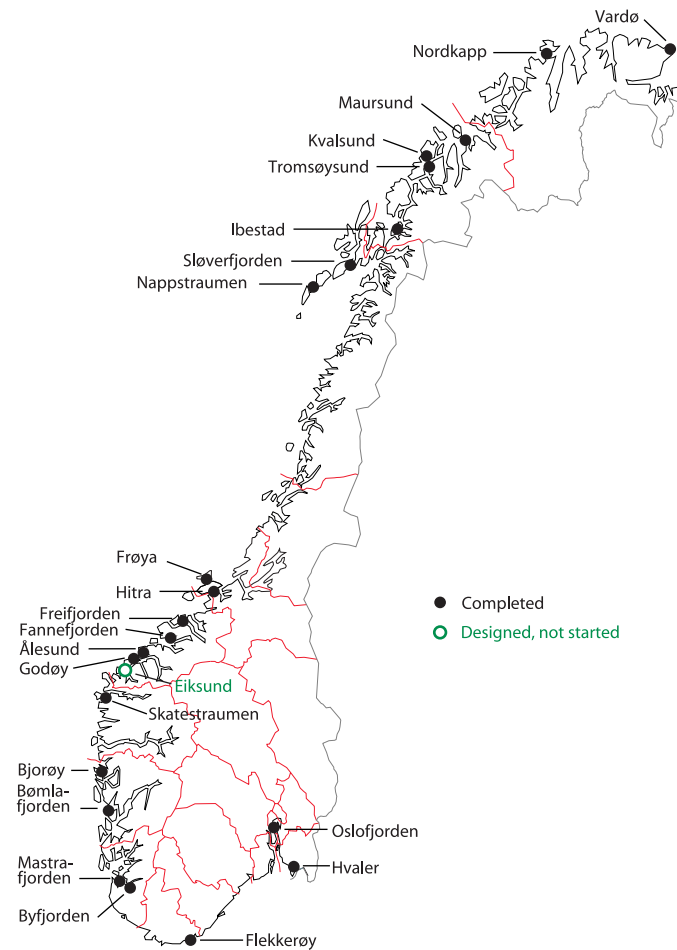


Figure 1: Map showing subsea tunnels.

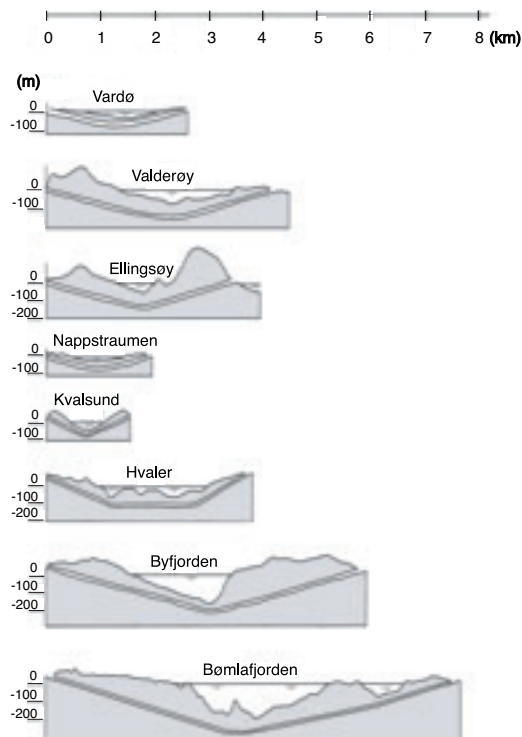


Figure 2: Length and depth of some subsea tunnels.



Are there any surprises to be expected in connection with extensive use of subsea tunnels?

2 Experience



The following tunnels are now in use:

Name	County	Road no.	Years of opening
Hvaler	Østfold	Rv 108	1989
Oslofjord	Akershus/Buskerud	Rv 23	2000
Flekkerøy	Vest-Agder	Rv 457	1989
Byfjord	Rogaland	Ev 39	1992
Mastrafjord	Rogaland	Ev 39	1992
Bjørøy	Hordaland	Fv 207	1996
Bømlafjord	Hordaland	Ev 10	2000
Fannefjord	Møre og Romsdal	Rv 64	1991
Freifjord	Møre og Romsdal	Rv 70	1992
Ellingsøy	Møre og Romsdal	Rv 658	1987
Valderøy	Møre og Romsdal	Rv 658	1987
Godøy	Møre og Romsdal	Rv 658	1989
Hitra	Sør-Trøndelag	Rv 714	1994
Frøya	Sør-Trøndelag	Rv 714	2000
Nappstraum	Nordland	Ev 10	1990
Sløverfjord	Nordland	Ev 10	1997
Tromsøysund*	Troms	Ev 8	1994
Kvalsund	Troms	Rv 863	1988
Maurusund	Troms	Rv 866	1991
Ibestad	Troms	Rv 848	2000
Vardø	Finnmark	Ev 75	1983
Nordkapp	Finnmark	Ev 69	1999

*) two tubes.

Traffic density varies considerably. Least traffic is found in the Bjorøy tunnel which connects a little island to the mainland, and in the Sløverfjord tunnel, where the amount of traffic is expected to increase significantly when the road project «Lofast», of which the tunnel is an integral part, is fully opened.

The following table shows traffic density, gradient and length of the tunnels that are now open for traffic:

Name	AADT	Maxgrade (%)	Length (m)	Greatest depth (m)
Hvaler	1 300	10	3 751	-120
Oslofjord	4 000	7	7 252	-134
Flekkerøy	1 060	10	2 327	-101
Byfjord	2 800	8	5 875	-223
Mastrafjord	3 000	8	4 424	-132
Bjorøy	350	10	2 000	-85
Bømlafjord	2 500	8.5	7 900	-260
Fannefjord	1 150	8.5	2 743	-100
Freifjord	1 850	9	5 086	-132
Ellingsøy	2 700	8.5	3 520	-140
Valderøy	2 250	8.5	4 222	-145
Godøy	725	10	3 844	-153
Hitra	635	10	5 645	-264
Frøya	530	10	5 305	-164
Nappstraum	600	8	1 780	-60
Sløverfjord	100	8	3 200	-100
Tromsøysund*	6 730	8	3 376	-101
Kvalsund	500	8	1 650	-56
Mårsund	600	10	2 122	-92
Ibestad	400	10	3 398	-112
Vardø	670	8	2 892	-88
Nordkapp	300	10	6 826	-212

*) two tubes.

2.1 Costs

Construction costs for the tunnels which are now open are shown in Figure 3.

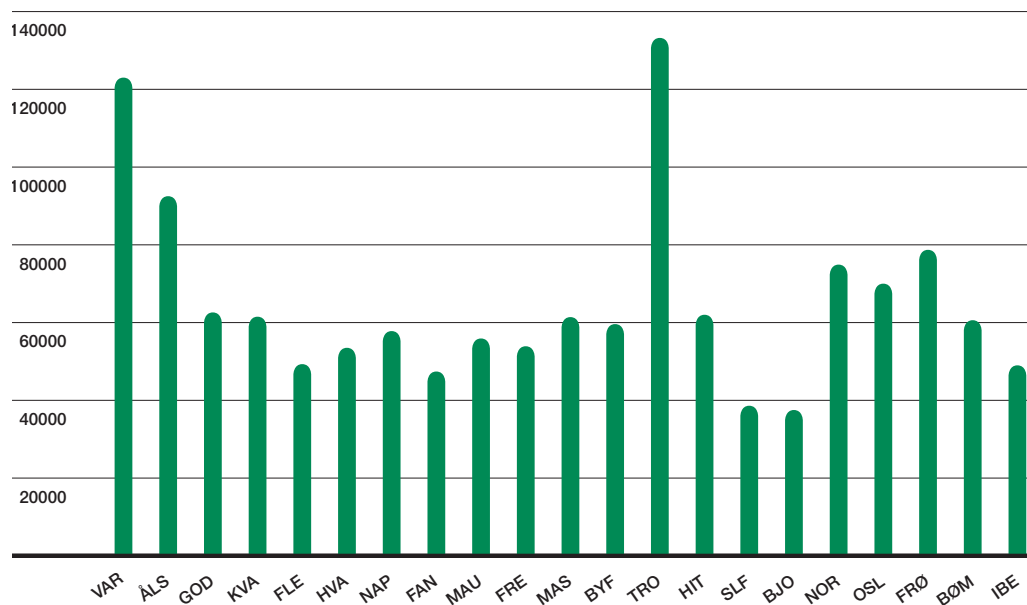


Figure 3: Total cost (NOK per metre).

All costs are based on 2000 costs, according to price indexes of the Ministry of Transportation and Communication.

From 1992 to 2000, prices have increased linearly by 37%. This is higher than the official price index. The reason for this is the improvement in tunnel standards, which is not compensated for in the Ministry's price index.

Costs for planning and field work are not included for all of the tunnels. It is estimated that these costs are somewhere between NOK 2000-4000 per metre tunnel. This does not apply to the last tunnels which have been completed, where all costs are included in the survey.

The total construction costs vary from NOK 35,000.- per metre to NOK 115,000.- per metre. The Tromsøsund tunnel is expensive because of its double tubes, whilst the Nordkapp tunnel is costly because of the poor rock quality in the tunnel.

The conclusions to be drawn from the figures above is that subsea tunnels have become cheaper, but that rock conditions for a particular tunnel are decisive for the final price.

2.2 Site investigations

Before the construction of a subsea tunnel, a geological site investigation has to be carried out. The investigation will determine the length and location of the tunnel. During the building period the nature of the preliminary investigations is carefully examined and compared with the last sample regularly taken along the proposed route of the tunnel.

A relatively simple geological investigation has been carried out for most tunnels, supplemented by acoustic measurements and seismic profiles where necessary. Rock core sampling from hard rock has only been used to a limited degree on a few projects. These relatively simple investigations worked satisfactorily until the construction of the Bjørøy tunnel. The same simple procedures were used here for the preliminary investigation. However, during construction, problems arose when a fault with younger rock had to be crossed. The fault was very difficult to work in, and made progress difficult for the contractor. At a later date problems arose in parts of the Nordkapp tunnel. The same occurred in the Oslofjord tunnel, where a fault filled with sand and gravel had to be frozen in order for the tunnel to be driven. These setbacks have resulted in more thorough preliminary investigations for new projects. Comprehensive rock sampling from bore holes were used in the preliminary site investigations for the Frøya and Eiksund tunnels. This is a complicated and lengthy process that can easily take several years to complete.

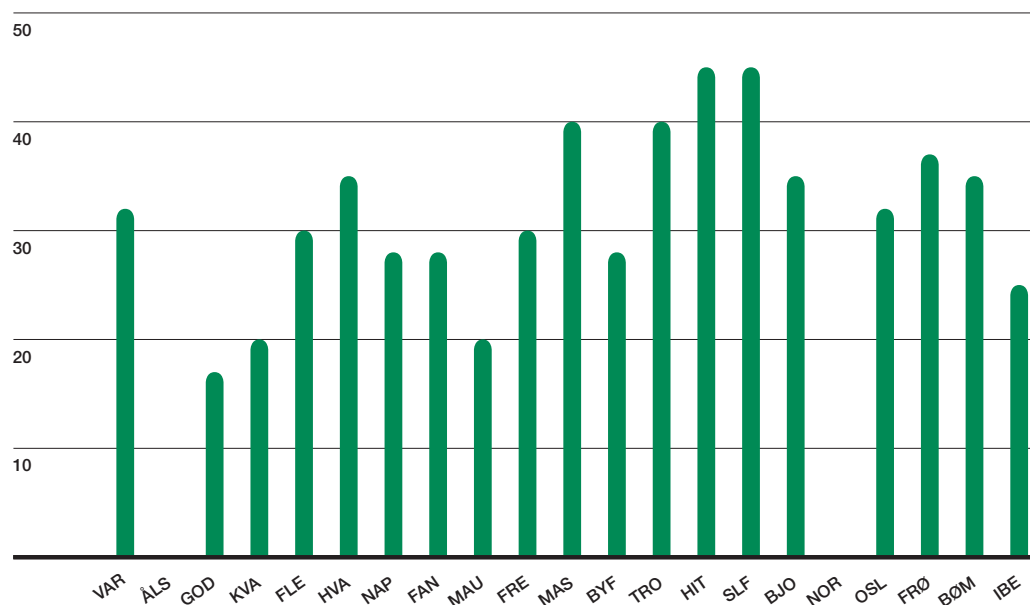


Figure 4: Minimum rock cover for constructed tunnels (metres).



Frozen sand, gravel and stones.

The minimum thickness of rock cover is a decisive factor for deciding tunnel length. The less cover permissible, the shorter the tunnel. However the chances for problems during construction increase with a reduction in cover. Thus minimum cover should not be less than 50 m, unless reliable investigations of the rock surface are available. Figure 4 shows the rock cover for the completed tunnels. As shown in the figure, as little rock cover as 20 m has been used. This must be regarded as being most audacious.

During the construction of the Oslofjord tunnel, a very weak fault was encountered 130 m below sea level. The fault was crossed by driving a pilot tunnel under the main tunnel-tube. The pilot tunnel was later incorporated in the drainage reservoir for leakage water. The work of boring freezing pipes through the fault took over a year. This is very complicated and expensive and should be avoided in future projects.

2.3 Construction



All Norwegian subsea road tunnels have been built by conventional drill and blast methods. Construction time is dependent on support measures that must be taken, and particularly those that have to be done at the tunnel face. In recent years, methods for shotcrete and concrete shuttering have been improved, so that these operations are both faster and give better results.

Bolting is the mostly used method of support, and is commonly used in conjunction with shotcrete. Figures 5 and 6 show the relationship between planned and actual amounts of bolting and shotcrete.

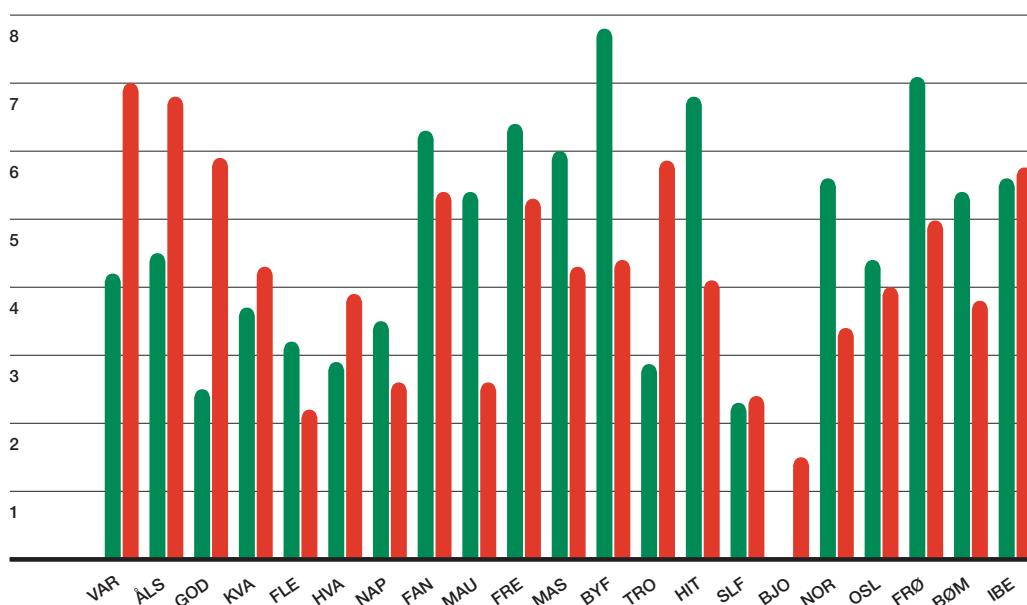


Figure 5: Bolting per metre tunnel: planned and executed (bolts/metre).
■ Planned ■ Done.

Bolting is the most popular support method used in Norway, and represents a high percent of the support costs, particularly at Vardø, Ålesund and Godøy.

The use of shotcrete has increased from about 0.7-1.0 m³/metre tunnel to about 1.5-2.0 m³/metre tunnel in some of the last tunnels completed. In the first tunnel, Vardø, concrete of C25 quality was used for temporary support. Experience has shown that C25 is of a too poor quality to use in tunnels, and it has now been replaced by C45 for shotcreting below sea level.

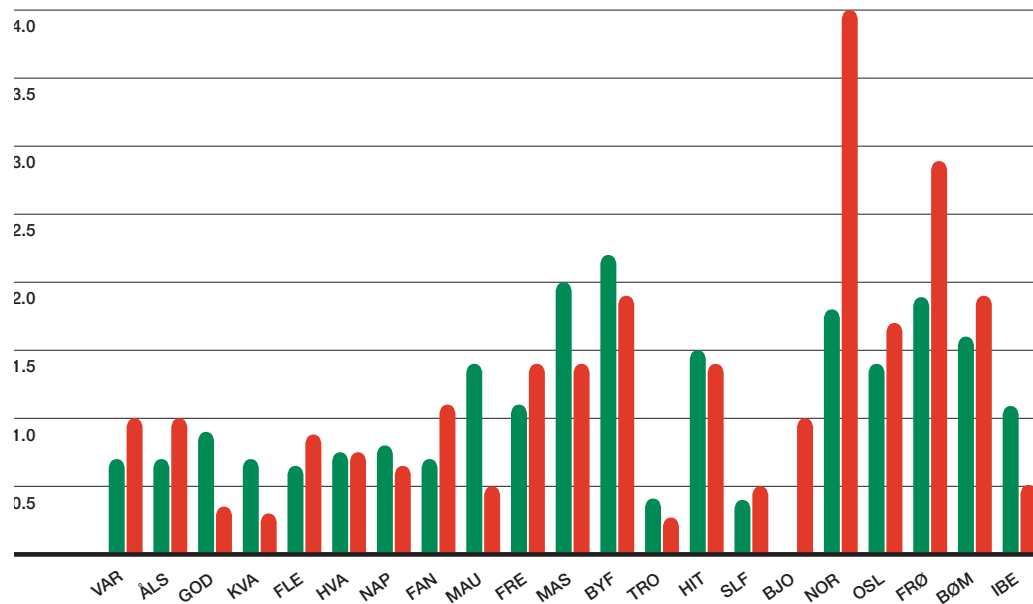


Figure 6: Shotcreting: planning and executed (m³/metre).
■ Planned ■ Done.

Initially, much use was made of concrete, but with time and experience, there has been a noticeable reduction in this expensive and time-consuming method. However, the Nordkapp tunnel is an exception to the rule, as the extremely poor rock conditions have resulted in almost 50% of the tunnel being lined with concrete. This also explains the high costs for the tunnel.



Shotcrete performance.

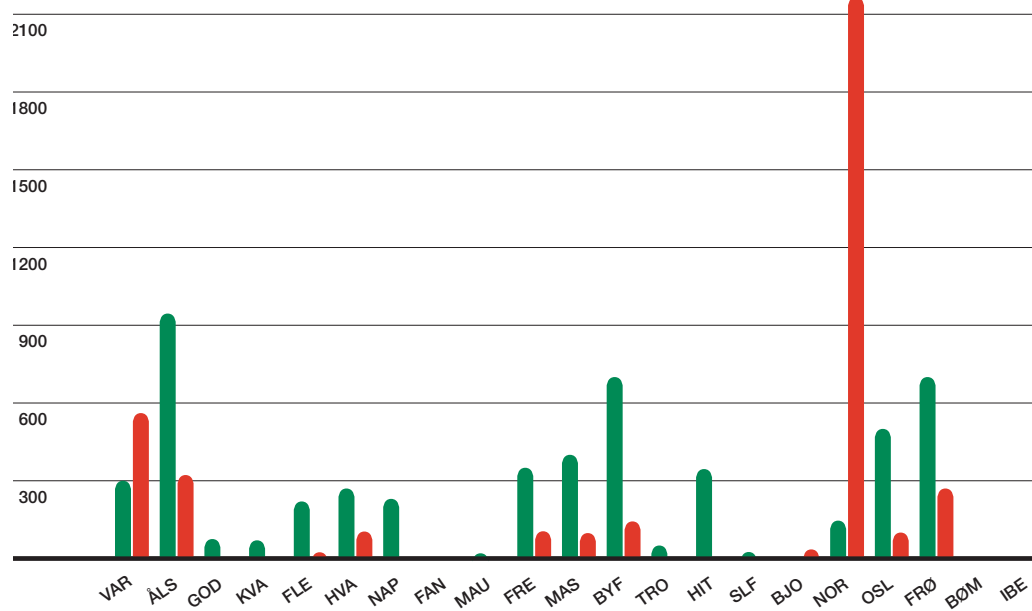


Figure 7: Concreting: planning and executed (metre).
■ Planned ■ Done.

Water ingress, and the need for its prevention is very difficult to ascertain prior to construction. Factors governing leakage are rock type, crack patterns and the amount of clay in the cracks.

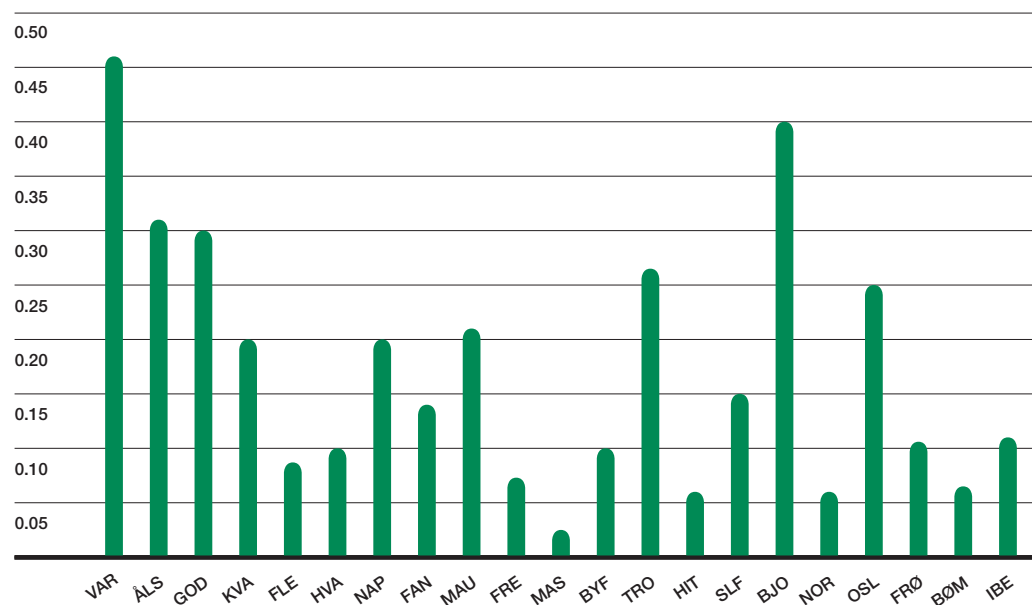


Figure 8: Water ingress at time of opening (litre/min/km).

Figure 8 shows the amount of leakage from each tunnel at the time of opening. This can be compared with the amount of injection that is shown in Figure 9. Up to the present time the Vardø tunnel has the highest leakage rate, but it must be said that it is also one of the tunnels with the least amount of injection.

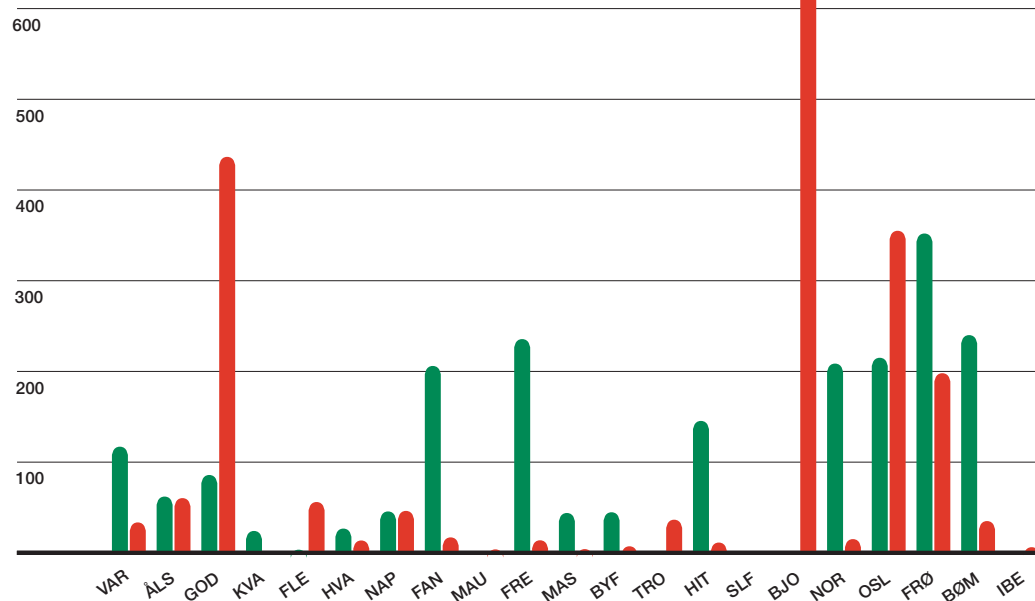


Figure 9: Injection: planned and executed (kg. per metre).
 ■ Planned ■ Done.

Figure 10 shows the amount of water/frost protection installed in Norwegian subsea tunnels. Apart from the large quantity used in Vardø and Ålesund, there is very little correlation between the quantity of water ingress and the amount of water/frost protection.

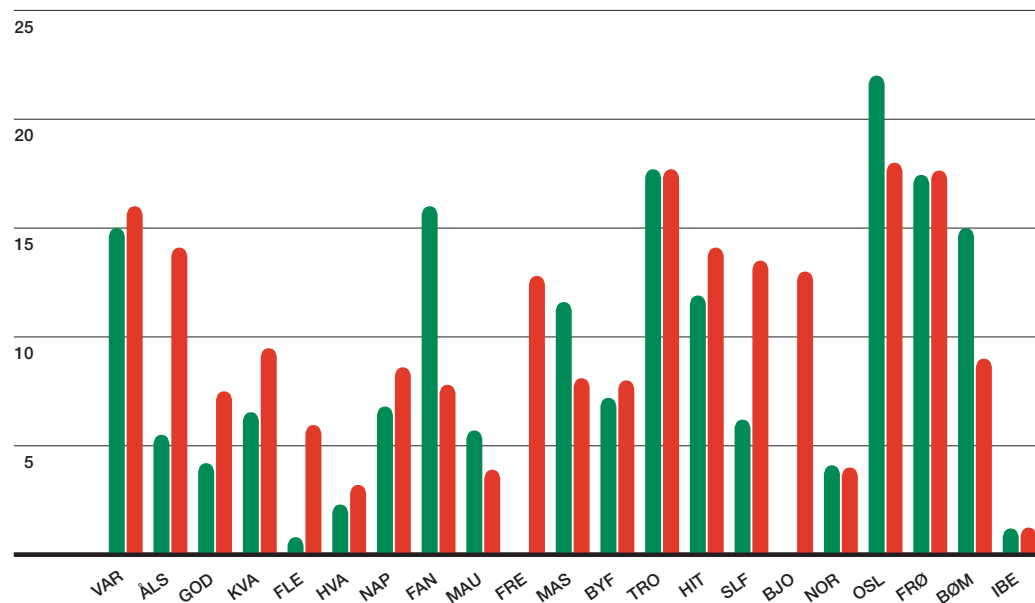
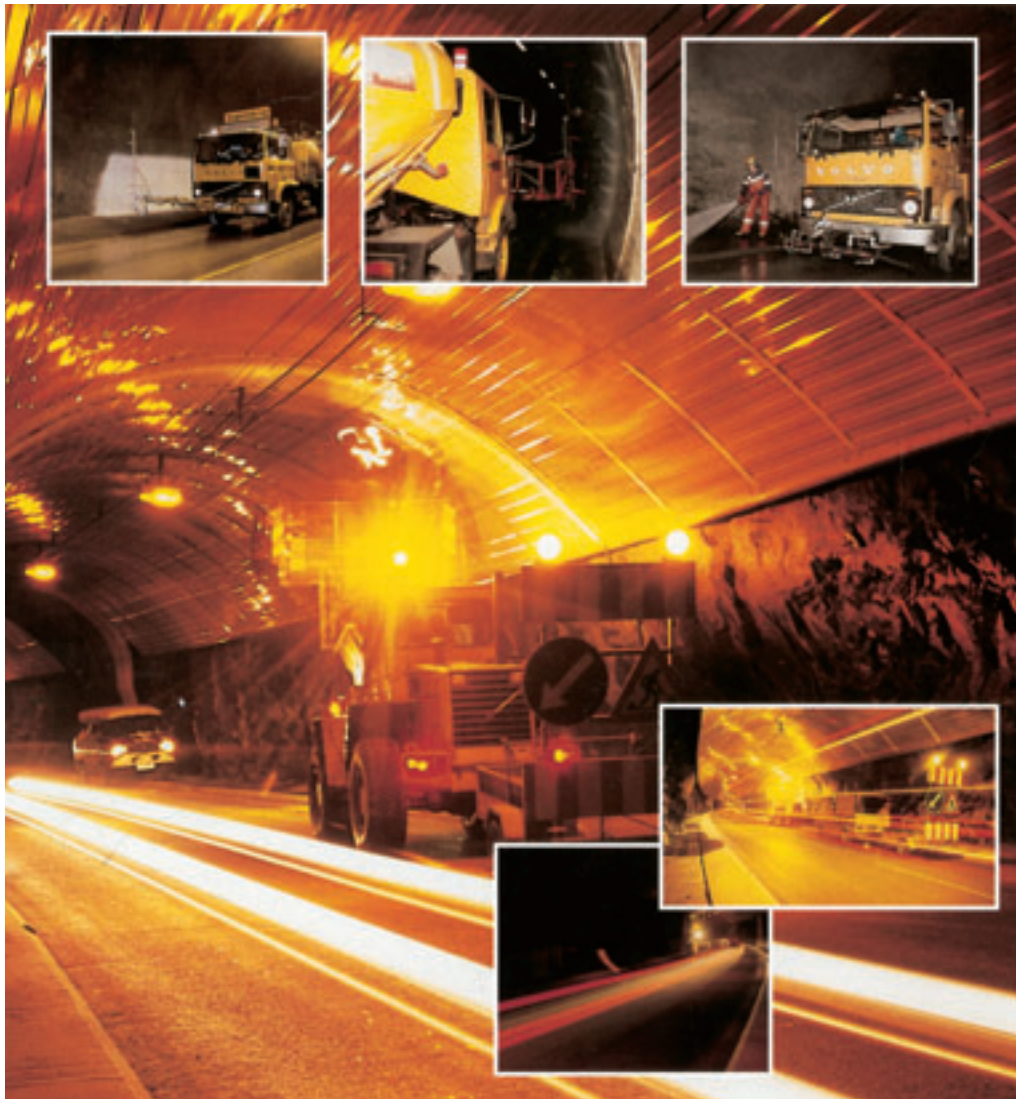


Figure 10: Protection against frost and water, planned and executed.
 ■ Planned ■ Done.

3 Operation and maintenance



3.1 Costs

When the tunnel at Vardø was opened, there was little relevant experience from operation and maintenance of subsea tunnels. One of the chief problems with the Vardø tunnel was too little capacity in the buffer reservoir for water leakages when the pumps broke down. Problems with emergency power, pumps and a special alga resulted also in high costs. Annual operation costs were more than NOK 1,000.- metre/year (in 2000 costs). These costs have now been considerably reduced.

The annual operative costs for some of the subsea tunnels are shown in Figure 11. As is apparent from the figure, there is a great variation between the tunnels. There are also large variations from year to year for any particular tunnel. This is dependent on the size of maintenance measures.

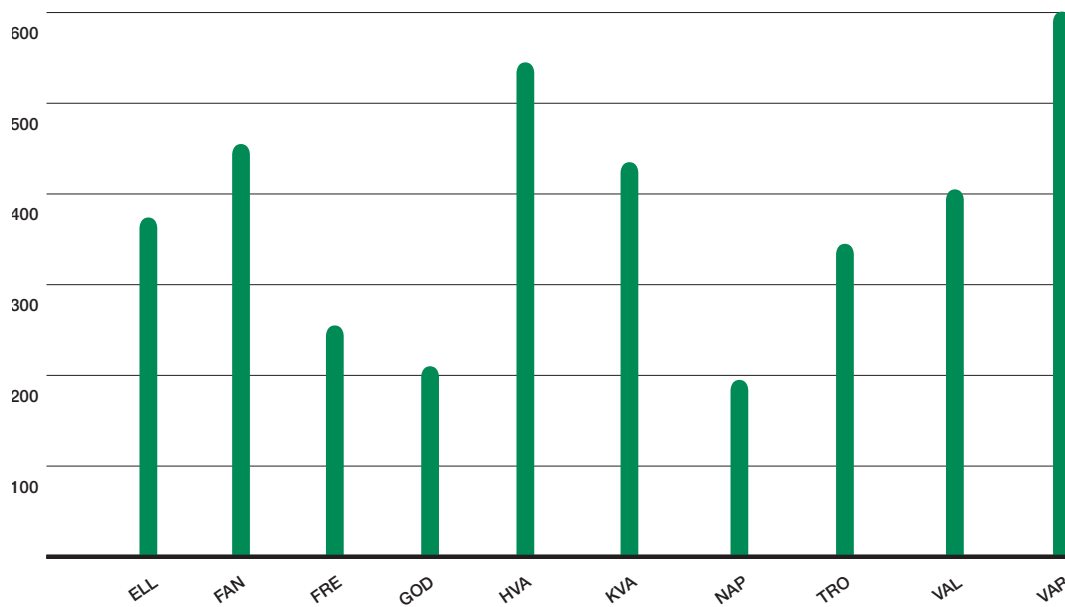


Figure 11: Operation and maintenance cost for some sub-sea tunnels (NOK/metre/year).

There are a number of installations in the tunnels that have to be periodically replaced. These include pumps, drainage pipes, electrical installations and water and frost linings. The annual costs for these items are only partially included in the above figures. The costs of improving and replacing installations in some of the tunnels can be quite expensive in the year it is effected.

Figure 12 illustrates this, and shows that reinvestment costs constitute a major part of the total annual costs. Costs for electricity represent between 25 and 50% of the annual costs as shown in Figure 13.

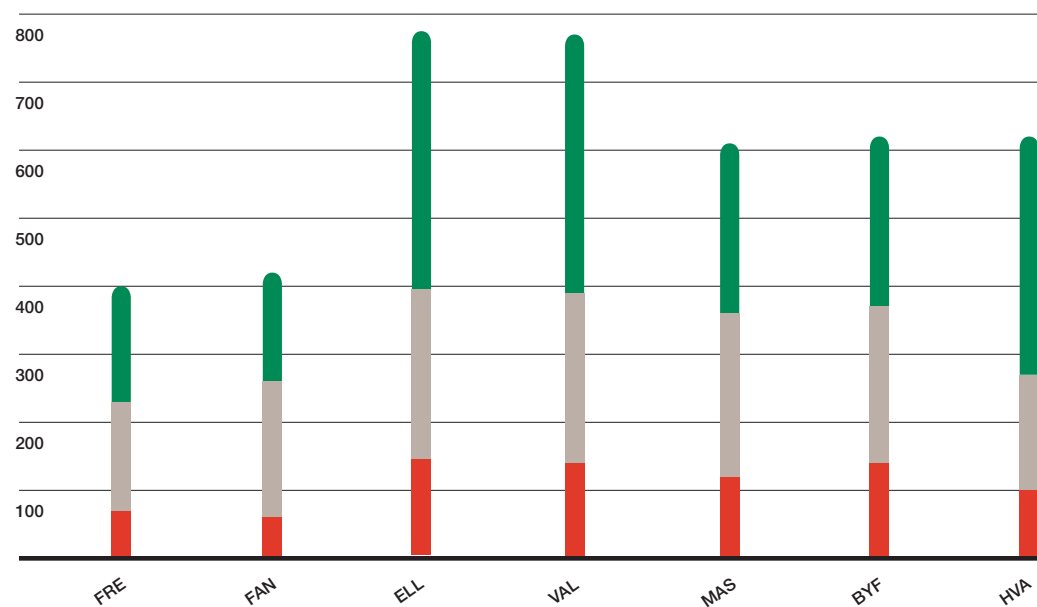


Figure12: Averagere investment, operation and maintenance cost for some subsea tunnels (NOK/metre/year).
 ■ Maintenance ■ Operation ■ Reinvestment.

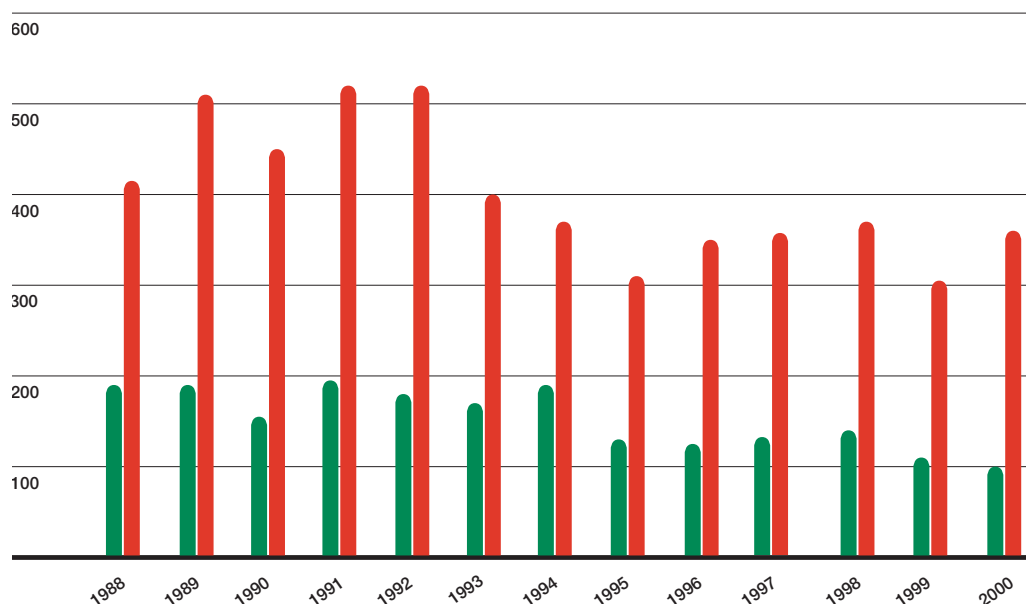


Figure 13: Total reinvestment, operation and maintenance cost for Ålesund subsea tunnels compared with electrical power supply costs for some years (in 2000 cost) (NOK/metre/year).
 ■ El. power supply ■ Total

The dominant operation and maintenance costs are attached to electrical power supply for lighting and ventilation. The cost of maintaining electrical installations can be high in individual tunnels.

Figure 14 shows how costs are distributed between lighting, ventilation, pumping and other uses in the Ålesund tunnels. Ventilation costs take the highest share.

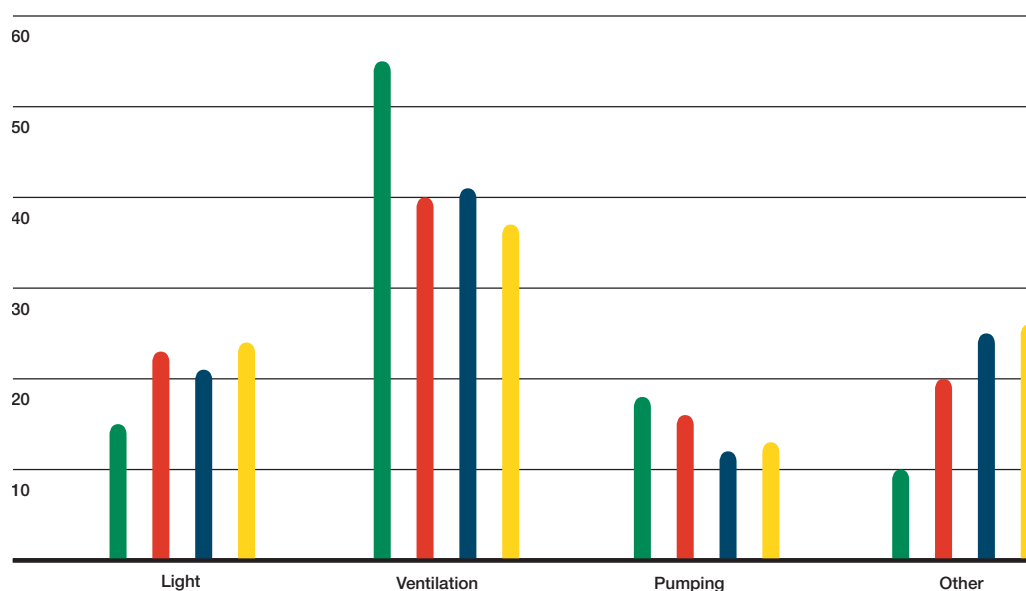


Figure 14: Typical electrical power supply cost in subsea tunnel, here Ålesund tunnels.
 ■ 1989 ■ 1993 ■ 1999 ■ 2000.



Pumping costs are relatively low. In virtually all subsea tunnels water leakages have been reduced after the tunnels have become operational. In some tunnels the reduction has been more than 50% in relation to initial leakages. It would appear that the tunnels have a certain self-sealing capacity.

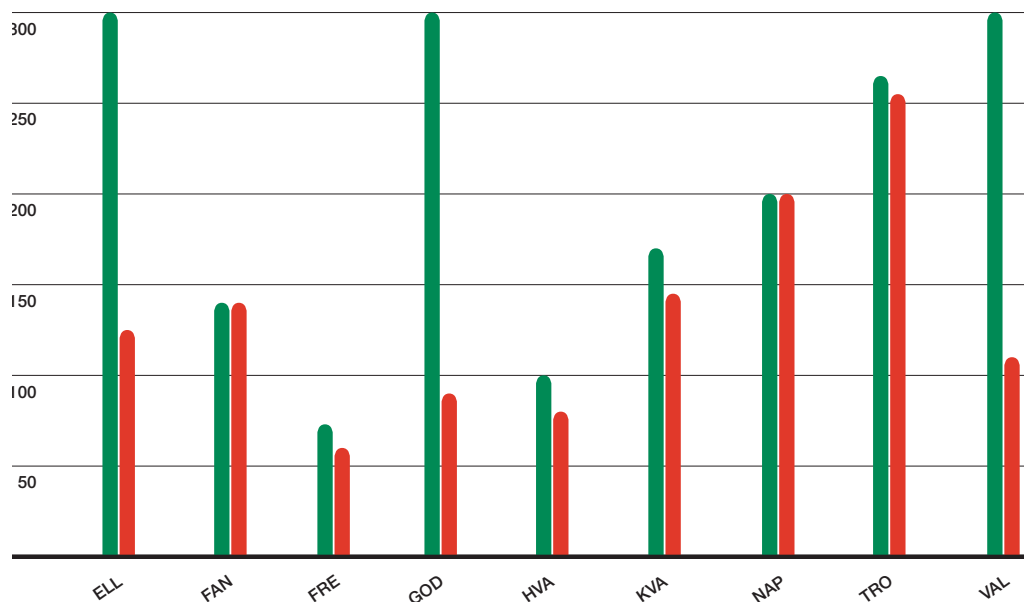


Figure 15: Leakage in some subsea tunnels in year of opening (page 8) and in 1996 (litre/min).
■ Year of opening ■ 1996.

Figure 15 shows the relationship between the leakages in the tunnel at the year of opening compared with those in 1996. Virtually all tunnels have reduced leakages, and none have increased leakages since they were opened. Figure 16 shows clearly how pumping time has been reduced from year to year. The most probable reason for this is that particles in the rock cracks move and reduce cavities, and that minerals in the rock swell and close the cracks.

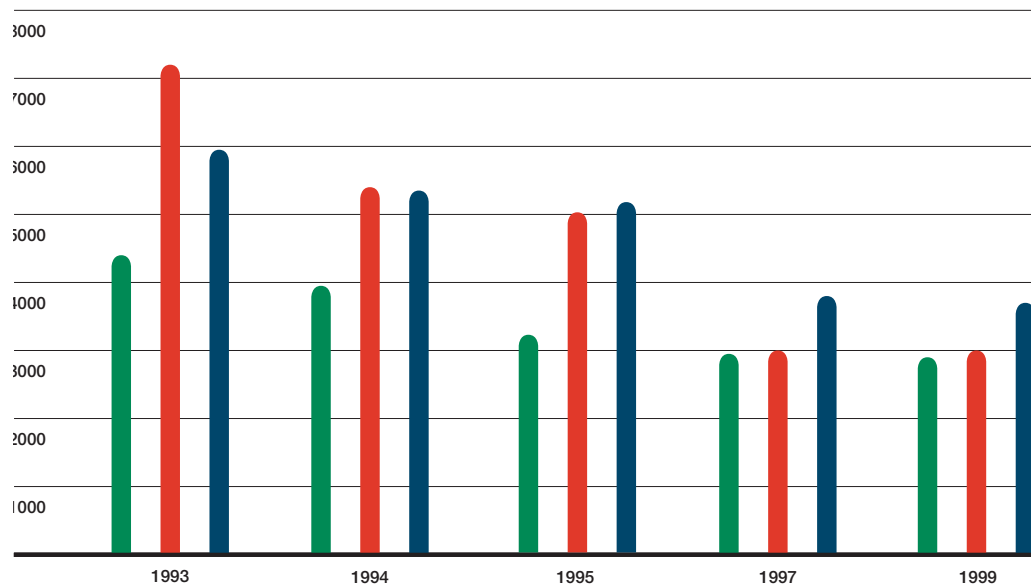


Figure 16: Pumping time in subsea tunnels for each year.
 ■ Ellingsøy ■ Valderøy ■ Godøy.

3.2 Other operational problems

The most extraordinary problem in subsea tunnels is algae. This phenomenon exists in a number of tunnels. It appears to be no connection between type of rock and the presence of algae. Experience, particularly from Vardø, would tend to suggest that the algae population expands to a certain level before collapsing and starting all over again.

Seawater leakages on the asphalt surface make the asphalt quite slippery, possibly because of the algae.

Shotcrete is broken down by seepage, particularly in salt water. Poor quality shotcrete is much more susceptible than high quality shotcrete. Consequently, new and more stringent rules have been made for the use of shotcrete in tunnels.

So far corrosion has not resulted in any great problems for subsea tunnels. However, electrical equipment, pumps and piping have had to be replaced in several tunnels because of corrosion. In future tunnels, more attention must be paid to the choice of corrosion resistant materials.

Damage to aluminium linings by salt water has been registered in the Freifjord and Fannefjord tunnels as well as in some others. The corrosion damage to the aluminium linings due to seawater is of such a scale that the linings must be replaced. Replacement work has already started at Freifjord and Fannefjord.

4 Traffic and fire safety, previous studies



Driver behaviour and traffic accidents are of major importance when designing and operating road tunnels. Insight into tunnel operation ensures that tunnels can be built to a high level of safety at reasonable cost. Applicable know-how on road tunnel safety in Norway is mainly based on a study from 1997.

The study is based on police-reported personal injury accidents in tunnels on the national road network. The precise location of all tunnels has been identified in the National Road Database. Output from this database on tunnels opened before 1992 and earlier was used for the study. A total of 587 tunnels was selected. According to official accident statistics, 492 accidents had been recorded in these tunnels during a five-year period. No personal injury accidents had been recorded in 388 (66%) of the tunnels.

Each tunnel was divided into 4 zones:

- zone 1: 50 m in front of the tunnel
- zone 2: the first 50 m of the tunnel
- zone 3: the next 100 m of the tunnel
- zone 4: covering the middle part of the tunnel.

26% of the accidents were recorded outside the tunnel (in zone 1), 19% in zone 2, 19% in zone 3 and 36% in zone 4. If we only look at accidents within the tunnel, 25% take place in the first 50 m, 25% in the next 100 m and 50% in the middle of the tunnel. Accident rates are 0.3 outside tunnels, 0.23 in the first 50 m within the tunnel, 0.16 for the next 100 m and 0.10 for the rest of the tunnel (accident rate = personal injury accidents per mill veh. km per year). Accident rate for the tunnel part was calculated to 0.13, which is less than the accident rate for similar roads in the open (0.15-0.20).

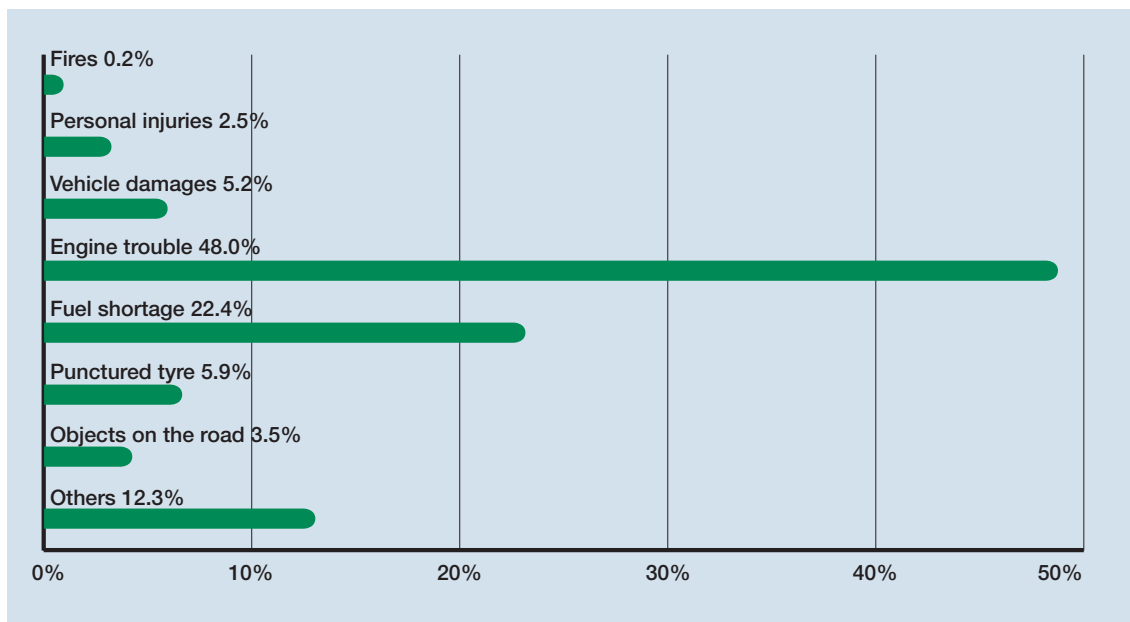
Accidents within tunnels are somewhat more severe than accidents on the open road network. The study shows that long tunnels are safer than short tunnels, even when taking into consideration that the entrance zones covers a greater part of the short than of the long tunnels. Accident rate in tunnels shorter than 100 m was calculated to 0.35 and the rate in tunnels longer than 3 km to 0.05.

Most of the accidents are of the same direction type (43.3%) and the single vehicle accident type (29.8%). These two types are found more often here than when compared with accidents on the open road network.

When comparing one and two-tube tunnels, it is necessary to remember that two-tube tunnels in the study material were shorter than the one-tube tunnels. When compensating for this, the difference is about 25-30% in favour of the dual tube tunnels.

There is no official reporting of fires in tunnels in Norway. A special study in 1997 indicated that there had been 41 fires in a seven-year period. No injuries were recorded in these fires. There had, however, been some fires caused by traffic accidents in which the car had started to burn after the accident. In such accidents serious injuries have taken place.

5 Accidents in subsea tunnels



Incidents in road tunnels.

This special study covers 17 of the subsea tunnels opened in 1996 or earlier. Data on five years of accidents recorded by the police was used. Specific data on the tunnels is shown in the table below.

Name	Length m	AADT	Gradient %
Byfjord	5875	2800	8
Hitra	5645	635	10
Freifjord	5086	1850	9
Mastrafjord	4424	3000	8
Valderøy	4222	2250	8.5
Godøy	3844	725	10
Hvaler	3751	1300	10
Ellingsøy	3520	2700	8.5
Tromsøysund*	3376	6730	8
Sløverfjord	3200	100	8
Vardø	2892	670	8
Fannefjord	2743	1150	8.5
Flekkerøy	2327	1060	10
Mårsund	2122	600	10
Bjørøy	2000	350	10
Nappstraumen	1780	600	8
Kvalsund	1650	500	8

*) two tubes.

Of the 17 tunnels in this study 9 were longer than 3.5 km and traffic were lower than 5000 AADT inn all tunnels. (The AADT in Tromsøysund is 3376 in each tube.) 6 of the tunnels have a gradient of 10% and 7 a gradient of 8%. This means that the sub-sea tunnels have low traffic, are fairly long and steep.

The next table shows the number of police reported personal injury accidents over a five-year period (1995-99) which have occurred in the tunnels.

Name	Number of reported accidents
Byfjord	2
Hitra	2
Freifjord	2
Mastrafjord	-
Valderøy	2
Godøy	2
Hvaler	4
Ellingsøy	2
Tromsøysund*	2
Sløverfjord	-
Vardø	-
Fannefjord	1
Flekkerøy	-
Maurusund	-
Bjørøy	-
Nappstraumen	-
Kvalsund	-

*) two tubes.

This shows that 19 personal injury accidents have been reported in the 17 tunnels. There have been no reported accidents in 8 of the tunnels. The mean accident rate for all tunnels has been calculated to 0.09 accidents per 1 mill veh/km/year. This is comparable to the interior accident rate of all tunnels in the study of 1997. The rate is lower than on open roads in Norway. The tunnel with the highest accident rate is the Hvaler subsea tunnel, where the rate is 0.45.

Only the Tromsøysund tunnel has two tubes with two lanes in each tube. The accident rate of this tunnel is as low as 0.05. Of the 16 tunnels with one tube, only 6 tunnels have an extra lane (three lanes) in the up- and downhill sections of the tunnels. The accident rate in these tunnels are 0.07. The rest of the tunnels (10) have two lanes through. The accident rate in these tunnels is as high as 0.31. However, it must be remembered that these tunnels often have low traffic, low geometrical standard and steep grades.

There were only reported accidents in tunnels longer than 3.5 km, except for one accident in the Fannefjord tunnel. The accident rate in these 9 long tunnels was 0.10.

The 7 tunnels with AADT over 1500 had an accident rate of 0.06, while the tunnels with less traffic had a rate of 0.21.

The 7 tunnels with a gradient of 9 or 10% had an accident rate of 0.18, while the tunnels with a gradient of 8 or 8.5% had an accident rate of 0.06.

Contrary to the experience from ordinary road tunnels, 18 of the 19 accidents took place in the interior of the tunnels. Usually the entrance zone is the most accident-prone zone of the tunnels.

The accidents are not exceptionally serious as only one accident involved fatalities, three involved very serious injuries and one serious injury. The other 14 accidents only involved minor injuries.

Of the 42 vehicles involved, 32 were private cars. Of the drivers of the private cars, 24 were younger than 39 years of age, 13 were from 18 to 24 years of age.

Of the accident types 6 were single vehicle accidents, 6 were of the same direction type and 4 involved meeting vehicles in the tunnel.

6 Fires in subsea tunnels



Reports of fires are collected from fire departments and from the five regional traffic control centres. As far as we know only 3 fires, all without injuries to persons are reported in Norwegian subsea tunnels. The first is recorded in the Vardø tunnel (in 1993), the next was a fire in a mobile crane in the newly opened Hitra tunnel (1995) and the last was a minor truck fire/smoke incident in the Oslofjordtunnel (2000).

On January 1, 1995 at 07.55 in the morning a fire erupted in the motor of a mobile crane moving through the Hitra subsea tunnel. The driver tried to put out the fire using a fire extinguisher from the tunnel. The heat and smoke generated was so extensive that attempts to put out the fire had to be given up. By 08.05 the Hitra fire department was alerted. One minute later the driver called to inform the local road garage about the fire, and they subsequently alerted Hitra and Orkla road stations. Personnel from a construction company at Sunde then drove to the tunnel and closed it. At 08.55 Snillfjord fire department arrived at the tunnel. At 09.05 Snillfjord fire department drove to the scene of the fire without being hampered by the smoke. Lacking fire prevention equipment they returned to the tunnel entrance. At 09.35 the ventilation fans were fully engaged and the fire was extinguished at 09.50.

7 Discussion of the results



These accidents in the 17 tunnels were studied during a five-year long period. During the period 19 personal injury accidents were recorded by the police. No accidents had been reported in 8 of the tunnels. The accident rate is defined as personal injury accidents per 1 mill vehicle kilometres per year, and was calculated to 0.09 for all the tunnels in the study. This is a very low rate, comparable to the accident rates of modern two lane highways without driveways, intersections at grade and with no pedestrian traffic. Only one of the accidents took place in the entrance zone of the tunnels. This is contrary to the experience for other normal tunnels. The reason for this could be that the driving speed is usually low when driving into or out of subsea tunnels with steep gradients.

Almost all accidents were reported in the 9 longest tunnels.

Even if the material is very small, it seems that tunnels with low traffic have a higher accident rate than tunnels with higher AADT (i.e. higher than 1500). This could also be due to the fact that low traffic tunnels usually have steeper gradients and lower geometric design.

The material tends to show that tunnels with steep gradient (9 or 10%) have almost three times the accident rate as tunnels with a gradient of 8 and 8.5%.

Most of the drivers of the private cars were young drivers. 13 of 32 were between 18 and 24 years old. The reason for this much higher amount of young drivers could be that they are inexperienced and often tend to drive faster than older more experienced drivers.



The work for improved tunnels will go on into the future.

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Pavement Division, Soil Mechanics Division, Concrete Division, Geology and Tunnel Division, Production Technology Division and International Division.

Fields of Operation

Activities are directed towards Research and Development, Information and Tutor, Consulting, Specifications and Guidelines, Testing and Design Approval within the fields of material testing and highway construction and maintenance.

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