THIRTY YEARS OF EXPERIENCE WITH SUBSEA ROAD TUNNELS IN NORWAY

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ABSTRACT

The first Norwegian subsea tunnel was opened in 1983. Subsequently, 31 other subsea tunnels have been built. As a result in the 2012 a total of 32 subsea tunnels with a total length more than 126 km are open to traffic. Some new are under construction and several other subsea tunnels are also in the process of being planned, including tunnels of up to 24 km length. Most of the tunnels have one tube with two lanes, but some tunnels have an extra lane (overtaking lane) when the gradient is more than 6 %. The subsea road tunnel projects are located on the trunk roads along the coast replacing often congested ferry connections, and establishing ferry-free connection from the main land to the communities. Experiences from these tunnels are the theme for this presentation, but also design criteria, safety aspects and construction methods. 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.

1 INTRODUCTION

There are more than 1000 road tunnels in Norway. Until the end of the seventies in the 20th century numerous large bridges were built over Norwegian fjords or between some of the many islands along the coast. As the bridge span and 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 (Figure 1) between 1979 and 1983. After the Vardø tunnel was opened in 1983, 31 others have been built and opened to traffic. Today we have about 126 km of subsea road tunnels in Norway.

Most of the tunnels have only one tube with two lanes, but some tunnels have an extra lane (overtaking lane) where there are steep gradients. Some of the tunnels have also two tubes.

Figure 2 shows the length and depth of some subsea tunnels in Norway.
Figure 1  Maps showing subsea tunnels

Figure 2  Lengths and depths of some subsea tunnels
2 EXPERIENCE

The following tunnels (Table 1) are now in use in Norway.
The annual average daily traffic (AADT) varies considerably from tunnel to tunnel, from AADT approximately 100 veh/day to 100000 veh/day.
The gradient in Norwegian subsea tunnels varies from 6% to 10%.
The following table shows also the length of the tunnels that are now open to traffic, AADT and the year of opening.

Table 1 Subsea tunnels that are in use in Norway

<table>
<thead>
<tr>
<th>Tunnel name</th>
<th>County</th>
<th>Road No.</th>
<th>Length (m)</th>
<th>AADT</th>
<th>Years of opening</th>
<th>For short</th>
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<tbody>
<tr>
<td>Hvaler</td>
<td>Østfold</td>
<td>Rv 108</td>
<td>3751</td>
<td>1300</td>
<td>1989</td>
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<tr>
<td>Oslofjord</td>
<td>Akershus/Buskerud</td>
<td>Rv 23</td>
<td>7252</td>
<td>6000</td>
<td>2000</td>
<td>OSL</td>
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<tr>
<td>Flekkerøy</td>
<td>Vest-Agder</td>
<td>Rv457</td>
<td>2327</td>
<td>1500</td>
<td>1989</td>
<td>FLE</td>
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<tr>
<td>Byfjorden</td>
<td>Rogaland</td>
<td>Ev 39</td>
<td>5875</td>
<td>3000</td>
<td>1992</td>
<td>BYF</td>
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<td>Mategori</td>
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<td>4424</td>
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<tr>
<td>Talgefjordtunnelen</td>
<td>Rogaland</td>
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<tr>
<td>Karmøyunnelen</td>
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<td>Bjørvåy</td>
<td>Hordaland</td>
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<td>2000</td>
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<td>2000</td>
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<td>Hordaland</td>
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<tr>
<td>Knappetunnelen</td>
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<td>Skateshavn</td>
<td>Sogn og Fjordane</td>
<td>RV 616</td>
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<td>250</td>
<td>2002</td>
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<td>Fannefjorden</td>
<td>More og Romsdal</td>
<td>Rv 64</td>
<td>2713</td>
<td>1500</td>
<td>1991</td>
<td>FAN</td>
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<td>Freifjord</td>
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<td>Atlanterhavstunnelen</td>
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<td>Hitra</td>
<td>Sør-Trøndelag</td>
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<td>5645</td>
<td>1100</td>
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<td>Froya</td>
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<td>Skansendalunnelen</td>
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<td>Rv 706</td>
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<td>8000</td>
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<td>Tromsøysund†</td>
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<td>Ev 8</td>
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<td>Varde</td>
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<td>700</td>
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<td>Nordkapp</td>
<td>Finnmark</td>
<td>Ev 69</td>
<td>6826</td>
<td>300</td>
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<td>NOR</td>
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<td>Bjørnvika</td>
<td>Oslo</td>
<td>E 18</td>
<td>1100</td>
<td>100000</td>
<td>2010</td>
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</table>
2.1 Construction Costs

The total construction costs to day, based on current technical requirements, typically vary from NOK 120 000 per meter per tube to NOK 180 000 per meter per tube, depending on size of the cross section and geological conditions. All costs are based on year 2012.

2.2 Operation and maintenance General

The most extraordinary problem in subsea tunnels is algae. This phenomenon exists in a number of tunnels. It appears to be no connection between types of rock and the presence of algae. Experience particularly from Vardø tunnel, 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. Materials for installations in subsea tunnels must be supplied in stainless steel.

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

2.3 Operation and maintenance Cost

When the first subsea tunnel at Vardø was opened in 1983, there was little relevant experiences from operation and maintenance of subsea tunnels. One of the main 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 1 600 per meter per year (costs in 2012). These costs have now been considerably reduced, but vary from tunnel to tunnel according to traffic volume, technical installations and type of lining.

Typical operation and maintenance cost is from NOK 400 to NOK 1500 per meter per tube per year, depending of tunnel length and traffic volume.
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 not included in operation and maintenance cost above. The costs of improving and replacing installations and water and frost linings in some of the tunnels can be quite expensive in the year it is affected.

The dominant operation and maintenance costs are attached to electrical power supply for lighting and ventilation.

Figure 3 shows how costs are distributed between lighting, ventilation, pumping and other uses in the Ålesund tunnels. Ventilation costs take the highest share.

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 water leakages. It would appear that the tunnels have a certain self-sealing capacity.

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.

### 3.0 GEOMETRIC DESIGN

#### 3.1 General

Tunnels are different from open roads in respect of conditions such as:
- little or no lateral movement
- other winter conditions
- regular lighting throughout the day and year, except from the entry zone
- difficulties in estimating gradients
- difficulties in estimating distance to vehicle in front
- other safety measures, breakdown services, etc.
These require that a number of design elements will differ to those of the open road. Maintenance and operations shall ensure a constant level of safety in the tunnel. Important elements in this connection are:

- selection of the appropriate construction method and equipment in the planning and construction phases
- uniform standard for tunnels along the same road with corresponding traffic type and volume.

The demands placed on standards increase correspondingly with traffic volume and tunnel length. Tunnels are therefore placed in categories which determine the required geometric specifications and features.

### 3.2 Selection of tunnel category

The traffic volume is normally given in AADT (Annual Average Daily Traffic volume). AADT is the total annual traffic a year divided by 365 and is given as the total traffic volume in both directions.

The tunnel category is determined according to the estimated traffic volume twenty years after opening, AADT(20).

Where the traffic volume varies throughout the day or over the year, or where there is considerable uncertainty in calculating AADT(20), the tunnel category may be based on selected criteria.

The tunnel categories are based upon traffic volume (AADT) and tunnel length (Km). (Figure 4). The tunnel categories are the basis for a specific cross-section, number of tubes, need for emergency lay-bys and turning points together with safety equipment.

Example: 2 x T9.5, means two tunnel tubes, each with a width of 9.5 m.

![Figure 4 Tunnel category](image)
3.3 Tunnel cross-sections

The tunnel cross-sections are designated according to the total width of the road surface (Figure 5). The vertical clearance requirements in tunnels are 4.6 m. The vertical clearance specifications apply to the vertical distance measured on the carriageway boundary. Normal cross-sections will be in excess of this to allow for:

- Extra clearance for subsequent road resurfacing, normal tolerance for tunnel linings, water and frost protection / concrete linings (total deviation = 0.1 m)
- Requirements for vertical clearance including kerbstone.

Normally the tunnel cross-section will also include space for traffic signs and technical installations. The need for extra width locally must be considered in each individual case. The minimum height for technical equipment must be 4.8 m above the carriageway. For laterally-mounted equipment such as traffic signs etc., the clearance must be individually determined.

With consideration to emergency exits laterally mounted signs should be placed such that the minimum height below the sign is at least 2.0 m.

![Diagram of tunnel cross-section](image)

**Figure 5. Cross-section**

3.4 Design and location of emergency lay-bys and turning points

Emergency lay-bys enable parking outside of the carriageway in the case of emergency. Emergency lay-bys are designed as in Figure 6. Turning points are built into two-way tunnels. Emergency lay-bys can also function as turning points for light vehicles. Turning points for heavy vehicles are designed as in Figure 7.
Technical equipment is located in separate niches with an enclosing wall along side the traffic lane. These niches should be located together with the emergency lay-bys. The distance between the lay-bys is determined by the tunnel category. The distances given are approximate. The location will depend upon the local circumstances including rock mechanics and geometric considerations. Further, consideration must be made to designing niches for several purposes (for example, technical room, pump station etc.). Deviations in location should be within ±50 m for emergency lay-bys and ±100 m for turning points.

Figure 6 Emergency lay-by

Figure 7 Tourning point

3.5 Vertical curves for subsea tunnels

The maximum gradient for subsea tunnels is shown in Figure 8. Where an overtaking lane is constructed, the values in Figure 8 may be increased by 1%. Tunnels with local characteristics and low traffic volume, together with urban tunnels outside the main road network, may be constructed with a gradient of up to 10% for subsea tunnels of local character and low traffic volume. The AADT values for one-way traffic in Figure 8 apply to both tunnel tubes in aggregate.
Figure 8 Permitted gradients for subsea tunnel

3.6 Overtaking lanes

The need for an overtaking lane is based upon estimated capacity. In tunnels with two-way traffic and a gradient of > 6% over a stretch exceeding 1 km, a separate overtaking lane shall be constructed when the AADT(20) is > 2500 vehicle/day.

4.0 INVESTIGATIONS

4.1 General

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 rocks 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, and 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 the new projects. Comprehensive rock sampling from boreholes was 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.

4.2 Rock cover for subsea tunnels

The minimum thickness of rock cover is a decisive factor for deciding tunnel length. The less cover is permissible, the shorter the tunnel is. However, the chances for problems during construction increase with a reduction in cover, and therefore a minimum rock cover should not be less than 50 m, unless reliable investigations of the rock surface are available and for rock of good stability and good quality.
5.0 CONSTRUCTION METHODS

Norwegian specifications are based on the drill and blast method, and we use mostly the bid – build model and unit price contracts for our tunnel projects. The Norwegian tunnelling method regards the rock that we are tunnelling in as a construction material, and support methods are determined by assessment of rock quality at the tunnel face. This implies that actual quantities may differ from the contract’s bill of quantities, and we require a flexible contract for adjusting quantities for both support ahead of the tunnel face and support measures, and a clause to adjust construction time accordingly.

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 better results are achieved. Bolting is the mostly used method of support and is commonly used in conjunction with shotcrete. Figure 9 and 10 shows the relationship between planned and actual amounts of bolting and shotcrete.

![Bolting per meter tunnel: planned and executed](image1)

**Fig.9** Bolting per meter tunnel: planned and executed

![Shotcreting: planning and executed](image2)

**Fig.10** Shotcreting: planning and executed
The use of shotcrete has increased from 0.7–1.0 m$^3$/m tunnel to 1.5–2.0 m$^3$/m tunnel in some of the last completed tunnels. 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.

Initially, much use was made of concrete lining, but with time and experience, there has been a noticeable reduction in this expensive and time-consuming method, figure 11. 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. Water ingress, and the need for its prevention is very difficult to ascertain prior to construction. Factors governing leakage are rock types, crack patterns and the amount of clay in the cracks. Figure 12 shows the amount of water leakage from each tunnel at the time of opening. This can be compared with the amount of injection that is shown in Figure 13. Up to the present time, the Vardø tunnel has the highest water leakage rate, but it must be said that it is also one of the tunnels with the least amount of injection.
Figure 13. Injection: planned and executed

Figure 14 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.

Fig.14  Lining - Protection against frost and water, planned and executed

6.0 SAFETY

6.1 General

The level of safety in a tunnel shall resemble that of the open road. Control that safety objectives have been achieved, are made with the aid of a risk analysis. The tunnel category determines the specifications of safety equipment in the tunnels. The tunnel categories are illustrated in Figure 4, Tunnels with a length of between 250 m and 500 m are placed in a tunnel category which is lower than that suggeste by the designed traffic volume. For tunnels shorter than 250 m, demands are made only upon lighting.

The principles for evacuation are based upon road-users making their way out on foot or using their own vehicle. In tunnels with two-way traffic, facilities shall be available allowing road users to
Tunnels with two parallel tubes, emergency escape is made through footway interconnections.

Figure 15 shows the safety equipment in various tunnel categories.

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>TUNNEL CATEGORY</th>
<th>NOTES</th>
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<td>• Obligatory&lt;br&gt;○ Evaluated</td>
<td>A B C D E F</td>
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<td>Emergency lay-bys</td>
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<td>See Ch. 4 “Geometric design”</td>
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<td>Turning points</td>
<td>○ ○ ○</td>
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<tr>
<td>Escape possibility by foot</td>
<td>○ ○</td>
<td>Interconnections every 250 m</td>
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<td>Power supply, lighting and ventilation</td>
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<td>Emergency power supply</td>
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<td>Lighting in the event of power failure&lt;br&gt;See Sections 602.204 and 1003.6</td>
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<td>Emergency exit lighting</td>
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<td>Approx. every 62.5 m. See Sec. 602.202</td>
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<td>Emergency Exit sign</td>
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<td>Also obligatory in other categories if the tunnel is constructed with alternative emergency exits, e.g., interconnections. See Sections 602.203</td>
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<td>Emergency telephones</td>
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<td>Category B: Approx. every 580 m¹&lt;br&gt;C: Approx. every 375 mⁱ&lt;br&gt;D: Approx. every 250 m (both sides)¹&lt;br&gt;E: Approx. every 500 m¹&lt;br&gt;F: Approx. every 210 m¹</td>
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<td>Fire extinguishers</td>
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<td>Category B: Approx. every 250 m²&lt;br&gt;C, D: Approx. every 280 m²&lt;br&gt;E: Approx. every 125 m¹&lt;br&gt;F: Approx. every 62.5 m¹</td>
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<td>Height control barrier</td>
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1) Emergency telephones and fire extinguishers additionally installed outside each tunnel entrance (See Section 414.2)
2) Fire extinguishers mounted on one side at given intervals. In addition, fire extinguishers are located together with all emergency telephones on the opposite side

Figure 15  Safety equipment in the various categories
A solid circle indicates that the stated equipment is obligatory. An open circle indicates that the need to install this equipment has to be considered, and the equipment shall only be installed if it can be documented that there are special circumstances which deem this necessary.

In Figures 16 and 17, the location of emergency lay-bys, emergency telephones and fire extinguishers are indicated, as an example for tunnel categories B and E. In addition, an emergency telephone and fire extinguishers shall be placed outside each tunnel opening.

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**Figure 16** Lay-bys and safety equipment, tunnel category B

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**Figure 17** Lay-bys and safety equipment, tunnel category E
7.0 TECHNICAL EQUIPMENT

7.1 Specifications for technical equipment

All equipment shall be CE approved. The lifespan must be evaluated for each individual component based on estimates of approximate lifespan costs. The atmosphere in the tunnel is corrosive. This is due to condensation arising from warm, damp air. The water may be weakly acid due to nitrous acid and nitric acid from the nitrous gases in the exhaust. Equipment must therefore be protected from corrosion or be constructed from corrosion-resistant materials such that the minimum recommended lifespan is achieved. In tunnel categories C, D, E and F, together with tunnels characterised by a particularly corrosive environment, (for example sub-sea tunnels), cable duct bridges and light fittings must be supplied in stainless steel.

7.2 Ventilation

In Norway we always use longitudinal ventilation system for road tunnels.

Mechanical longitudinal ventilation is based on the use of impulse ventilator fans. In long tunnels and those with a high traffic volume, or where specific pollution regulations apply in the areas around the tunnel entrances, ventilation with the aid of a ventilation shaft will be appropriate.

The ventilation equipment shall be designed to cope with expected pollution levels 10 years after opening of the tunnel (AADT(10)). With a normal mixture of exhaust gases it is only necessary to determine the level of permissible concentration of carbon monoxide (CO-gas) and nitrogen dioxide (NO₂ gas). The concentration of the other toxic gases does not present a health hazard if a sufficient dilution of CO and NO₂ gases is achieved. In order to attain sufficient control of gas concentration in the tunnel, measuring instruments should be installed in the middle of the tunnel and at both ends. In one-way tunnels, measuring equipment is not required in the entrance zone.

The measurement range for CO shall be a minimum of 0–300 ppm and 0–25 ppm for NO₂.

A system of longitudinal ventilation may be constructed with or without ventilation shaft/side-adit. The air flow may be calculated as pipe flow and a simple equation for air movement in the tunnel may be formulated.

The forces which generate ventilation in a tunnel are of three types:
* mechanical ventilation force
* meteorological ventilation force
* piston effect from vehicles.
7.3 Fire ventilation

Where ventilation equipment is installed in a tunnel, this must be designed with regard to fire ventilation requirements. In the event of fire and smoke, the air speed should be able to be reduced to the lowest possible speed, yet sufficient to direct the smoke in the desired direction.
The ventilation direction will be determined in consultation with the fire authorities and incorporated into an emergency plan.
The ventilation equipment must be designed so as to be able to control a fire from 20 MW to 100 MW, dependent upon the tunnel category.
In order to achieve the necessary control of air flow in the tunnel, the ventilation shall be designed such that:
• it has the capacity to counteract the build-up of pressure in the tunnel.
On account of the general upward buoyancy, external wind and the fire itself, together with natural draughts on account of temperature differences inside and outside the tunnel.
• sufficient capacity is ensured in the ventilation equipment for the necessary time for the tunnel to be evacuated.

REFERENCES

(1) This paper is based on a publication about subsea road tunnels in Norway from year 2002. The title of the publication is “Publication no. 98, Subsea road tunnels in Norway” of Directorate of Public Roads, Road Technology Department.
(2) Handbook 021 Vegtunneler (2010), and English version handbook 021 Road tunnels (2004)
(3) Experiences with subsea road tunnels in Norway – construction, operation, costs and maintenance, Henning Jan Eirik, Melby Karl, Øvstedal Eirik, Amundsen Finn H.Ranes Guro (The Norwegian Public Roads Administration, Norway)