Summary

Vehicle fires in Norwegian road tunnels 2008-2015

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Norway is one of the countries that constructs the most road tunnels, and there are well over 1,100 in the country. Road tunnels are usually at least as safe as, or safer than similar roads in the open air, but they have a disaster potential related to vehicle fires. The report maps and describes the characteristics of fires and smoke without fire (SWF) in Norwegian road tunnels in the period 2008-2015. The average number of fires in Norwegian road tunnels is 0.02 fires per year per tunnel kilometres (24 fires per year per 1,134 tunnel kilometres). The average number of SWFs is 0.01 per year per tunnel km (14 SWFs per year per 1,134 tunnel kilometres). The study provides four main results. The first is that the fires and SWFs generally did not involve harm to people or tunnels. Of the 303 fires and instances of SWF, we know that 15 involved minor injury to people, 13 involved serious personal injury and eight involved death. All deaths and 10 of 13 serious personal injuries are related to fires and SWFs caused by traffic accidents. Seven large-scale tunnel fires in the period 2008-2015 caused smoke contamination for a total of 76 people. 92 of the 303 fires involved damage to vehicles and 33 involved damage to tunnels. The second main finding is that heavy vehicles are overrepresented in fires in Norwegian road tunnels. The third main finding is that the causes of road tunnel fires involving heavy (>3.5t) and light vehicles are different. Technical problems was a more than twice as frequent cause of fires and instances of SWF in heavy vehicles, than in light vehicles. The fourth key finding is that subsea road tunnels are overrepresented in the statistics of fires in Norwegian road tunnels. There are 33 subsea road tunnels in Norway. These have a high gradient, defined as over 5 %. In addition, there are 24 tunnels that are not subsea, but still have a high gradient. These 57 road tunnels, which together constitute 5 % of road tunnels in Norway, had 42 % of the fires and the instances of SWF in the period 2008-2015. Heavy vehicles were overrepresented in these fires, and technical problems were the most frequent cause. We discuss seven potential causes of the high number of fires in subsea road tunnels, and discuss the development in the four subsea road tunnels that have had the highest number of fires in the period.

Background and goal

Norway is one of the countries that constructs the most road tunnels. There are well over 1,100 in the country, comprising a total of 1,134 tunnel kilometres. Road tunnels are usually at least as safe as or safer than similar roads in the open air without junctions, exits, pedestrians and bicyclists. Road tunnels do nevertheless deserve attention from a traffic safety perspective, because of their disaster potential related to vehicle fires.

The goal with this project has been to collect data on fires in Norwegian road tunnels 2008-2015. We have previously mapped road tunnel fires for the period 2008-2011 (Nævestad & Meyer 2012). In the current report we provide an update of this study by including four years (2012-2015) in order to conduct a comprehensive analysis of all the data for the period 2008-2015. We have therefore used the data sources that we describe below twice.

Data sources and methods

1) "Vegloggen", which is the five Norwegian road traffic centrals' (RTC) systems for recording road traffic-related events. There are five RTC's in Norway, corresponding to the five regions of the Norwegian Public roads Administration. "Vegloggen" generally has good data about the tunnels in which vehicle fires occurred, the time when the fires occurred, the number of vehicles involved, how long tunnels have been closed because of fires, harm to people and tunnels induced by the fires, and how the RTC's were alerted about the fires.

"Vegloggen" frequently lacks information about where in tunnels the fires occurred, damage to vehicles and how the fires were extinguished. It often also lacks data on the causes of the fires. The data on use of fire ventilation is also of varying quality. Some regions, however, have done a better job registering this than others.

Vegloggen has no criteria when it comes to defining fires and separating them from instances of smoke without fire (SWF). In order to avoid confusion and minimize our discernments regarding which cases that are fires and not, we define all instances of open flame in vehicles as fires. We have, however, also included instances of SWF, as these also involve temporarily closed road tunnels. We exclude instances of SWF that could clearly not have turned into fire (e.g. fog, exhaust smoke, moist).

2) Road traffic central staff. While "Vegloggen" has provided us with knowledge about the prevalence of fires and SWFs, meetings and discussions with staff at the RTC's served to ensure the quality of our interpretations and to supplement our data. We have previously been given tours at three of the RTC's and received comprehensive information on the systems that they use to oversee and control the traffic and the road tunnels.

3) Employees of the Public Roads Administration working on tunnel safety. We communicated with fire and safety inspectors responsible for road tunnels in each region. These supplemented and assured our data.

4) Fire services. Fire services and other emergency services are called out on suspicion of fires in road tunnels and record such call-outs over time. We cooperated with the Directorate for Civil Protection and Emergency Planning (DSB) in our inquiries to the fire services. In the last study, we also compared our own data with the DSB's own road tunnel fire statistics, obtained through their BRIS system.

5) News archives. We have also searched news archives to supplement our data collection. Road tunnel fires are extensively covered by local newspapers and often also by the national media. In several cases where we lacked information, we got supplemental or explanatory information, often from photos obtained from for example the search engine of "www.google.no". This data source has been very important to us.

Quality assurance. In this project we have received data on road tunnel fires from each region. We have read through the records of a large number of events from the RTC's, and coded or standardized each event in spreadsheets to analyse data in our data analysis programs. We have also received information from fire departments about several of these events. When we had coded all data for a region into a spreadsheet, we sent it back to our contact person at the RTC', fire managers and tunnel safety inspectors in the respective region for quality assurance.

The number of fires and SWFs peaked in 2011

The data shows that the average number of fires in Norwegian road tunnels is 24 per year per 1,134 tunnel kilometres, and that the average number of SWF is 14 per year per 1,134 tunnel kilometres. This means that there are 0.02 fire per year per tunnel km and 0.01 SWFs per year per tunnel km.

These events are unevenly distributed in the different regions. The average number of fires and SWF per year is 9 in the eastern region, 4 in the southern region, 14 in the western region, 9 in the central region and 3 in northern region. The eastern region has over 90 tunnels, the southern region has over 140 tunnels, the western region has over 560 tunnels, the central region has over 150 tunnels and the northern region has over 180 tunnels.The relatively high number of fires and SWFs in the eastern region is probably due to the fact that this region has a high traffic volume.

The number of fires and SWFs peaked in 2011; with a total of 48 events. There were 47 events in 2013. The annual number of events was reduced since then, to 36 in 2015. We have suggested that the development in the period 2008-2015 can be interpreted in at least three different ways: 1) As a gradual increase in events with some annual variation, 2) that 2011 represented a maximum year and that the number of fires and SWF is decreasing since then, or 3) that we only see random fluctuations in our study period. Calculation of significance levels for the number of fires and SWFs per 1,134 road tunnel kilometre per year shows that the number of fires and SWFs in 2011 was significantly higher (P=0.02) than in 2008. The differences between 2008 and 2015 and 2011 and 2015 were not statistically significant.This indicates that a combination of hypothesis 2 and 3; meaning that 2011 was a peak year and that we besides from that see variation, but not a decrease which is statistically significant. It must be pointed out, however, that the average number of events was 34 from 2008 to 2011, while it was 42 in the period 2012-2015. This may indicate a gradual increase between 2008-2015. On the other hand, the number of events decreased again in 2015.

New data in the years to come will provide us the answer as to which of the hypotheses that are most credible. Finally, it is important to note that the numbers are small, and that our calculations of significance levels ideally should have included the numbers of vehicle kilometres in road tunnels in Norway per year. We have unfortunately been unable to conduct such calculations, but our numbers can provide the basis for such calculations in future research.

It is interesting to see that we have not had a clear increase in the number of fires and SWFs every year in the period, considering that the number of tunnels increases every year (with perhaps 10 to 20 tunnel kilometers), while the volume of traffic also increases slightly each year (perhaps 1-2 %).

Looking at the development in the five regions of the Norwegian Public Roads Administrations, it seems that the western region has had an increase in fires in tunnels in the period 2009-2015. The number of fires varies however substantially each year in the different regions. The central region seems to have had an increase in the number of SWFs in the period 2008-2013, but the number has decreased since then. The number of SWFs also varies substantially each year in the different regions. A chi-square analysis focusing on fires/SWFs for the years 2008-2015 in all the regions indicates that the distribution of fires/SWFs not is significantly different from a random distribution.

The fires generally did not involve harm to people

The study provides four main results. The first is that the fires generally did not involve harm to people or tunnels. In over 83 % and over 81 % of the cases, the fires involved no harm to people or tunnels respectively. The situations is different with respect to damage to vehicles, where the outcome in 49 % of the cases is recorded as "unclear". Of the 303 fires and instances of SWF, we know that 15 involved minor injury to people, 13 involved serious personal injury and eight involved death. All deaths and 10 of 13 serious personal injuries are related to fires and SWFs caused by traffic accidents. 92 of the 303 fires involved damage to vehicles and 33 involved damage to tunnels.

Although we conclude that the fires and SWFs mainly not involve personal injury, it is important to point out that the largest fires involve smoke contamination. Seven major fires during the period 2008-2015 led to smoke contamination for a total of 76 people: Skatestraumtunnelen, 15.07.2015; Brattlitunnelen, 17.01.2013; Gudvangatunnelen, 05.08.2013; Gudvangatunnelen, 11.08.2015; Oslofjordtunnelen, 23.06.2011; Oslofjordtunnelen, 29.03.2011 and Operatunnelen, 14.06.2015.

Heavy vehicles are overrepresented

The second main finding is that heavy vehicles are overrepresented in road tunnel fires. 40 % of the fires involved heavy vehicle(s) (> 3.5 tonnes), while 58 % of the fires involved vehicles < 3,5 tonnes. This indicates that heavy vehicles are overrepresented in road tunnel fires, as they on average constitute 14 % of the traffic volume on Norwegian state roads with road tunnels. This finding is in accordance with both Norwegian and international research. A share of 91 % (110) of the heavy vehicle fires and SWFs involved heavy goods vehicles, while 9 % (11) involved buses.

Different causes of fires involving heavy and light vehicles

The third main finding is that the causes of fires in heavy and light vehicles are different. Traffic accidents (single vehicle accidents and collisions) seem to be a rarer cause than technical problems (33 %) when we look at all the fires and instances of SWF in the period 2008-2015. More than half of all instances (54 %) has an unclear cause. This is probably due to inadequate reporting. The second most common cause is technical problems (33 %), followed by single vehicle accidents (5 %) and collisions (8 %).

The categories of causes are however different when we compare fires and instances of SWF involving heavy vehicles and light vehicles. Table S1 shows the causes of fires and SWF for vehicles under and over 3.5 tonnes, in Norway 2008-2015.

Table S.1: the causes of fires and smoke without fire for vehicles under and over 3.5 tonnes, in Norway 2008-2051 (N= 291).

Causes	Vehicles <3,5 t	Vehicles >3,5 t	Number of incidents:
Unclear	61 %	41 %	154
Technical problems	20 %	52 %	95
Single accidents	8 %	1 %	15
Collision	11 %	7 %	27
Number of incidents	175	116	291

Table S.1 shows that technical problems was a more than twice as frequent cause of fires and instances of smoke without fire in heavy vehicles, than in light vehicles. The table also shows that traffic accidents (single vehicle accidents and collisions) was twice as frequent as a cause of fires in light vehicles than in heavy vehicles.

The majority of the fires and the instances of SWF did, as mentioned, not involve personal injuries. It is nevertheless of vital importance to gain insights into the causes of the instances that did involve personal injuries in order to prevent these in the future.

Table S2 shows the causes of road tunnel fires and instances of SWF, involving personal injury in Norway, 2008-2015.

Table S.2: The causes of road tunnel fires and instances of smoke without fire, involving personal injury in Norway, 2008-2015 (N= 298).

Causes	No injury	Unclear	Minor injury	Serious injury/death	Number of incidents
Unclear	91 %	5 %	2 %	1 %	100 %
Technical problems	91 %	2 %	6 %	1 %	100 %
Single accidents	36 %	0 %	14 %	50 %	100 %
Collision	17 %	26 %	13 %	44 %	100 %
Number of incidents	247	16	15	20	298

Table S.2 shows that most of the fires involving personal injuries are caused by single accidents and collisions. Single accidents caused personal injuries or deaths in 64 % of the instances, while collisions caused personal injuries or deaths in 57 % of the instances. Technical problems caused minor injuries in 6 % of the fires.

Subsea road tunnels

The fourth main finding of our study is that subsea road tunnels are considerably overrepresented in the fire and SWF statistics in Norway. No other country has more subsea road tunnels than Norway.

There are 33 subsea road tunnels in Norway: The eastern region has three, the southern region has one, the western region has 10, the central region has 10 and the northern region has 9 subsea tunnels. In addition, there are 24 tunnels that are not subsea, but have a high gradient (defined as over 5 %) in the western region. Since the degree of gradient appears to increase the risk of fire, we include these 24 road tunnels in the analyses.

There are thus at least 57 road tunnels in Norway with high gradient. These represent approximately 5 % of the road tunnels in Norway, and 14.5 % of the tunnel kilometres in Norway (165/1134). These tunnels had 42 % of the fires in the period 2008-2015.

The annual number of fires and SWF per year per km tunnel in Norway in general is 0.03 (38/1134). However, we can distinguish between fires and SWF in tunnels with high gradient and without high gradient. The former has an average of 15.9 fires and SWF per year (127/8), while the latter has 22 fires and SWF per year (176/8). This gives 0.1 fires and SWFs per year per tunnel km with high gradient (15.9/165) versus 0.02 fires and SWFs per year per tunnel km without high gradient (22/969). The former are, in other words 5 times more exposed to fires. Thus, subsea road tunnels are significantly overrepresented in the statistics of fires in Norwegian road tunnels in 2008-2015.

Heavy vehicles are over-represented in fires in tunnels with high gradient. There is a significant relationship between subsea tunnels and the proportion of heavy vehicles involved in fires. Figure S1 shows the involvement of heavy vehicles in fires and instances of SWF in non-subsea tunnel fires and subsea tunnel fires, 2008-2015. Both shares of heavy vehicles in fires and SWF, 35 % in non-subsea tunnels and 46 % in subsea tunnel fires, indicate that heavy vehicles are overrepresented in road tunnel fires, but that this especially applies to subsea road tunnels.

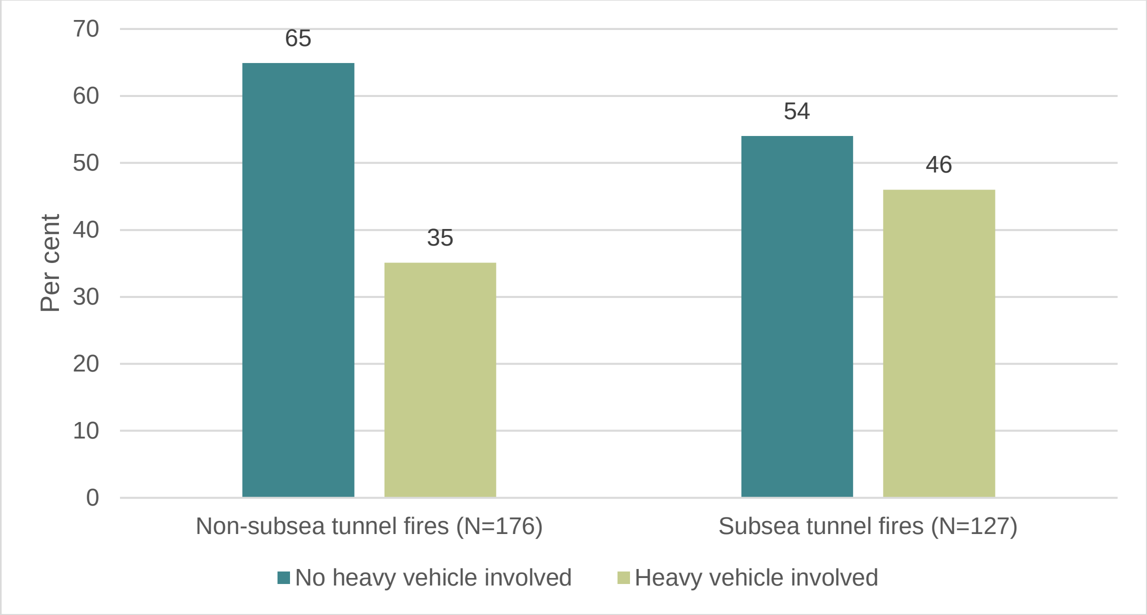

Figure S.1: Heavy vehicle involvement in non-subsea tunnel fires (N=176) and subsea tunnel fires (N=127), 2008-2015. Percentages based on the number of fires in subsea tunnels and other tunnels.

The considerable proportion of heavy vehicles involved in fires in subsea tunnels is in line with the causal picture presented in the report of the "Søndre Follo" fire service on the fire in the "Oslofjordtunnel" 23.06.2011. Previous Norwegian studies also show that the proportion of heavy vehicles involved in tunnel accidents are twice as high as the traffic volume and the proportion of accidents on open roads would suggest.

Figure S.2 shows the causes of fires and instances of SWF in non-subsea tunnels and subsea tunnels. The percentages are based on the number of fires in tunnels that are non-subsea and subsea, in Norway 2008-2015.

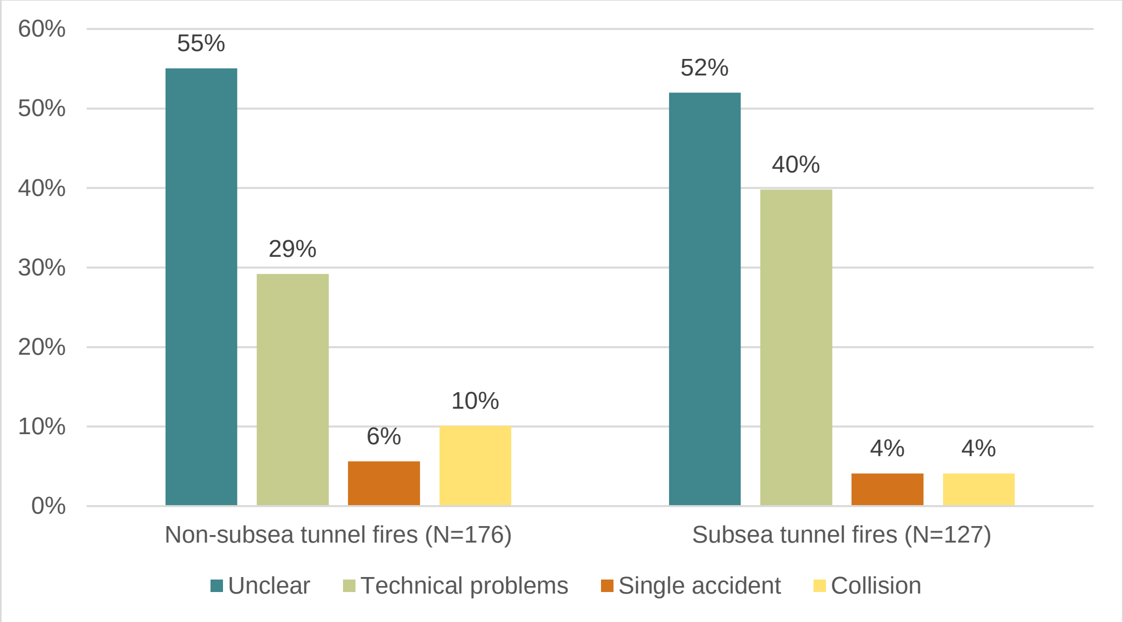

Figure S.2: The causes of road tunnel fires and instances of smoke without fire in non-subsea tunnels and subsea tunnels, 2008-2015. Percentages based on the number of fires and instances of smoke without fire in other tunnels (N=176) and subsea tunnels (N=127).

Figure S.2 indicates that technical problems is a more frequent cause of fires in subsea tunnels than it is in tunnels without a high gradient. Figure S.2 also shows that single accidents and collisions seem to be a twice as important cause of fires and SWF in non-subsea tunnels as in subsea tunnels (16 % vs. 8 %). By far, the most important cause of fires in subsea tunnels is technical problems. However, it is difficult to draw conclusions about this, since the cause is unclear in as many as 50 % of the fires.

We have analyzed the development in the annual number of fires and SWFs in subsea road tunnels in the period 2008-2015. The analyses do not seem to indicate an increase in the number of fires and SWFs in these tunnels in the period 2008-2015, rather a variation around an annual average of 16.

When and where do the fires occur?

An analysis of the fires and SWF in Norway 2008-2015 shows that 44 % of the fires 2008-2011 occurred in the afternoon. 65 % of the fires occurred between 06 and 18. The majority, or 57 % of the fires occurred in the spring and summer. June is the month with most fires (13 %). November is the month with the fewest fires (5 %).

In 36 % of the instances we lacked data on how the fire was extinguished, in 42 % of the cases, the fire services extinguished the fires, and in 19 % of the cases the driver extinguished the fires. In 4 % of the cases other road users extinguished.

In the last study of road tunnel fires (2012-2015), we have included information about whether fire extinguishers were removed from the fire cabinets in the tunnels during the fires (N=164). This was done in 45 of 164 cases in the period: 29 % of the cases involved heavy vehicles, while 71 % involved cars (<3,5 t). Fire extinguishers were especially removed when the fires were extinguished by the drivers or other road users. Most of the fires are registered in the middle zone of the tunnels.

The length of time the tunnels have been closed due to fire, group themselves into two parts. The first is between 1 and 45 minutes (40 %), and the other is 106 minutes or more (17 %).

We lack data on how the RTCs were alarmed about the fires in 14 % of the cases. The police (24 %) and road users represent the most frequent actor to warn the RTC's of road tunnel fires. Combining the two options that road users can warn their local RTC about road tunnel fires (own telephone and tunnel telephone), we get a share of 24 %. 21 % of the fires were reported by means of automatic alarm in road tunnels. Fire services notified about the fires in 15 % of the cases. The fire warning technology in road tunnels fills an important function. If we combine the shares of automatic tunnel fire detection and warnings communicated by means of tunnel telephone, we get a share of 33 %.

Suggestions for further research

Calculating the risk of vehicle fires in road tunnels

Road tunnel fires are rare occurrences, and if we had included all the events that are not ending in fires, and compared the characteristics of them with the characteristics of the fires, we could perhaps have calculated the risk and the risk factors of tunnel fires. The units in the present study have however been fires and SWFs, and we have not been able to conduct proper estimations of the factors predicting the outcome road tunnel fire compared to other outcomes.

We may, however, still use our data to assess whether some characteristics seem to be overrepresented in road tunnel fires. In this way we may point to specific risk factors related to tunnel fires, such as subsea tunnels, high gradient and heavy vehicles.

The numbers from the study can be used to calculate the risk of fires of vehicles over 3.5 tonnes and below 3.5 tonnes, in road tunnels generally and in subsea tunnels specifically. This can be done by taking traffic volume into the calculations, like for instance Haack (2002) does in his calculation of fire risk in German road tunnels.

We suggest that it also may be interesting to study the prevalence, causes and risk of vehicle fire in heavy vehicles on long road stretches of open air road with high gradient. This may provide us with a better numerical base and possibilities for drawing conclusions on risk factors and possible measures.

Potential causal mechanisms behind vehicle fires in subsea tunnels

In the following we will discuss the possible causes as to why it appears that the risk of vehicle fires is higher in subsea tunnels. These are also questions for future research.

1) High gradient. A first key factor is the high gradient of subsea road tunnels. The European Union's tunnel directive 2004/54/EC, "Minimum safety requirements for tunnels in the Trans-European Road Network (TERN)" permits a maximum gradient of 5 % in TERN road tunnels. This directive is implemented as a provision to the Norwegian Road Act, limiting the gradient in non-subsea road tunnels to 5 % (Buvik 2012).

However, because of the unique Norwegian topography with very deep fjords, the EU has accepted that Norway may have different regulations for maximum gradient in subsea tunnels. As a consequence, the Norwegian tunnel provision previously stated that the gradient may be more than 5 % when other solutions are geographically impossible. This applied to subsea road tunnels. In the new Handbook N500 Road tunnels, which applies from November 2016, the possibility to construct high gradient tunnels is, however, limited to a maximum gradient of 5 %.

2) Heavy vehicles' brakes or engines? The investigation report of the fire brigade of "Søndre Follo" (2011) following the Oslofjord tunnel fire 23.06.2011 shows that the Oslofjord tunnel experienced 11 fires in the three years preceding the 23.06.2011 fire. Eight of the fires were in heavy vehicles, while three of the fires were in passenger cars.

This report is important, as it suggests that the steep gradient in this subsea road tunnel seems to involve a higher vehicle fire risk for heavy vehicles. The Oslofjord tunnel, which is 7,250 metres long, has two stretches of about 3,000 metres, each with a gradient of 7 %. Two thirds of the fires in the heavy vehicles were caused by overheated brakes as heavy vehicles drove down into the tunnel, while one third was caused by overheated engines as heavy vehicles drove up and out of the tunnel (Søndre Follo Brannvesen 2011: 9; cf. Safetec 2011).

Although we have to be careful to conclude due to small numbers, the report indicates that the problem of overheating is most critical when heavy vehicles drive downhill into tunnels, i.e. related to braking. We have tried to follow up through examining the causes of fires and SWF in subsea road tunnels involving heavy vehicles in the period 2012-2015.

In the years 2012-2015 there were 63 fires and incidents of SWF in subsea road tunnels and other road tunnels with high gradients in Norway, 23 of which involved heavy vehicles. When we look at these 23 events, we see that 10 of them are in various ways associated with technical issues related to the engine, and to a lesser extent to overheating of brakes or bearings as described in the Southern Follo Fire Department's report.

Table S.3: Causes of 23 fires and SWF involving heavy vehicles in subsea road tunnels in the period 2012-2015.

Causes	Cases
Motor (e.g. turbo)	5
Oil spill, oil leakage, other motor leakage	5
Wheels (Brakes/bearings/tyres)	2
Other technical	2
Unknown	9
Total 2012-2015	23

The share of unknown causes is substantial, however, and we need more research on the causes of these events. Given the importance of technical problems as the cause of fire, future research should focus on expanding knowledge about the importance of different types of technical failure as the cause of fires in heavy (and light) vehicles. The importance of vehicle-technical risk factors may for example be studied by measuring the temperature in the brakes and vulnerable engine parts during operation in various subsea road tunnels, or open-air sections with different types of heavy vehicles. Thus, one might be able to determine the significance of the vehicle's weight and braking system (for example: type of engine brake, retarder) year etc., combined with tunnel characteristics (gradient and length), the importance of driving style and the importance of different brake types.

3) Tunnel length. A third factor which could be important for the higher vehicle fire risk of subsea tunnels is tunnel length. Subsea road tunnels are on average four times longer than Norwegian road tunnels in general. This is however not sufficient to explain the overrepresentation of subsea tunnels when it comes to vehicle fires. We have seen that overheating because of gradient seems to be the most important cause of vehicle fires in subsea road tunnels. This indicates that the gradient and the length of the gradient are important.

4) Distance with high gradient. A fourth factor which seems to contribute to the higher vehicle fire risk of subsea tunnels is the distance with a high gradient (Buvik, Amundsen & Fransplass 2012). As noted, the vehicle fire prone "Oslofjordtunnelen" (N=16) has two stretches of about 3,000 metres with a 7 % gradient. There are especially three other subsea road tunnels in Norway contributing to the over-representation of subsea tunnels when it comes to fires in the period 2008-2015. The first is "Byfjordtunnelen" with 16 fires, a length of 5875 metres and a 8 % maximum gradient. The second is "Bømlafjordtunnelen" with 14 fires, a length of 7,888 metres and a 8.5 % maximum gradient. The third is "Eiksundtunnelen" with 10 fires, a length of 7,765 metres and a 9.6 % maximum gradient. We return to these tunnels below.

5) Traffic volume and share of heavy vehicles. A fourth factor which should be considered when discussing the higher vehicle fire risk of subsea tunnels is traffic volume and share of heavy vehicles. Road tunnels with more traffic have more fires (OECD 2006) and we have seen that heavy vehicles have a higher fire risk in subsea tunnels. Thus, we should perhaps expect that subsea road tunnels have high traffic volumes and high shares of heavy vehicles. However, when we look at the four subsea tunnels which had 44 % of the subsea road tunnel fires in our study, we see with one exception that none of them exceeded the average heavy vehicle share of 14 % on Norwegian state roads. We also see that the AADTs of these four tunnels are lower than the average number of 10,000 on Norwegian state roads

6) Vehicle type, age and standard. A sixth factor which could be important for the higher vehicle fire risk of subsea tunnels is vehicle type, age and standard. Discussing the influence of technology, Safetec (2011) states that the foreign (especially eastern European) lorries have two axles, weaker engines and they are generally older than Norwegian lorries. The lower technical standard of European lorries from the new EU member countries is also highlighted in an OECD (2006: 12) publication on road tunnel fire risk in the EU, which states that the share of older lorries is higher in these countries. It has also been asserted that older European heavy vehicles often lack motor brakes, so called retarder (Buvik, Amundsen & Fransplass 2012).

The demands on the foreign lorries increase when they are used with heavy loads in hilly terrain. This applies to Scandinavian terrain in general, but especially steep subsea road tunnels. On the other hand, it must be noted the heavy vehicles from the EU have a lower maximum load than Norwegian heavy vehicles (40 vs. 50 tonnes) (Buvik 2012). This should reduce the risk of overload in hilly terrain.

7) Heavy vehicle drivers' experience and competence. A seventh factor which could be important for the higher vehicle fire risk of subsea tunnels is driver competence and experience. This is also underlined in the Safetec (2011) risk analysis. Discussing the influence of competence and experience, Safetec suggests that Scandinavian lorry drivers probably have more experience and competence with regard to driving on Norwegian roads. As a consequence, they probably apply the brakes more correctly driving downhill in road tunnels, minimizing the risk of overheated brakes.

Future studies should examine the importance of heavy vehicle drivers' skills and experience when it comes to both causing and preventing fires and SWF in hilly terrain and not least what preventive measures can be taken. One possible approach is interviews with professional drivers, relevant experts and organizations on both the employer and employee side.

We can probably learn more about the actual causal mechanisms through interviewing drivers about the kind of factors that come into play when driving on roads with high gradient, the competencies required to do this safely, the equipment required (engine brake, retarder), their experience with this, not to mention what measures they believe will be effective. An important additional question may be whether foreign professional drivers have the competence and equipment necessary (ref. Safetec 2011; Nævestad et al 2016).

Four subsea road tunnels with a high number of fires

In the previous survey (Nævestad & Meyer 2012) we concluded that a small number of subsea tunnels in the eastern, western and central regions caused subsea tunnels to be overrepresented when it comes to fires and SWFs in the period 2008-2011. These tunnels were: 1) Oslofjordtunnelen, 2) Byfjordtunnelen, 3) Bømlafjordtunnelen and 4) Eiksundtunnelen.

In the present study we find that these four tunnels have had 44 % (56 of 127) of the fires and SWFs in subsea road tunnels in the period 2008-2015. They had 57 % of the events of 2008-2012, so the number of incidents in these four tunnels has decreased in the period 2012-2015. This is due not least to developments in two tunnels: Oslofjordtunnelen and Eiksundtunnelen. These had a total of 17 events in the period 2008-2011, as compared to nine in the period 2012-2015. Figure S.3 indicates a gradual reduction of the number of incidents in the two tunnels through the period. We know that several measures have been implemented in Oslofjordtunnelen since the fire 23.06.2011, especially aimed at reducing fire risk for heavy vehicles.

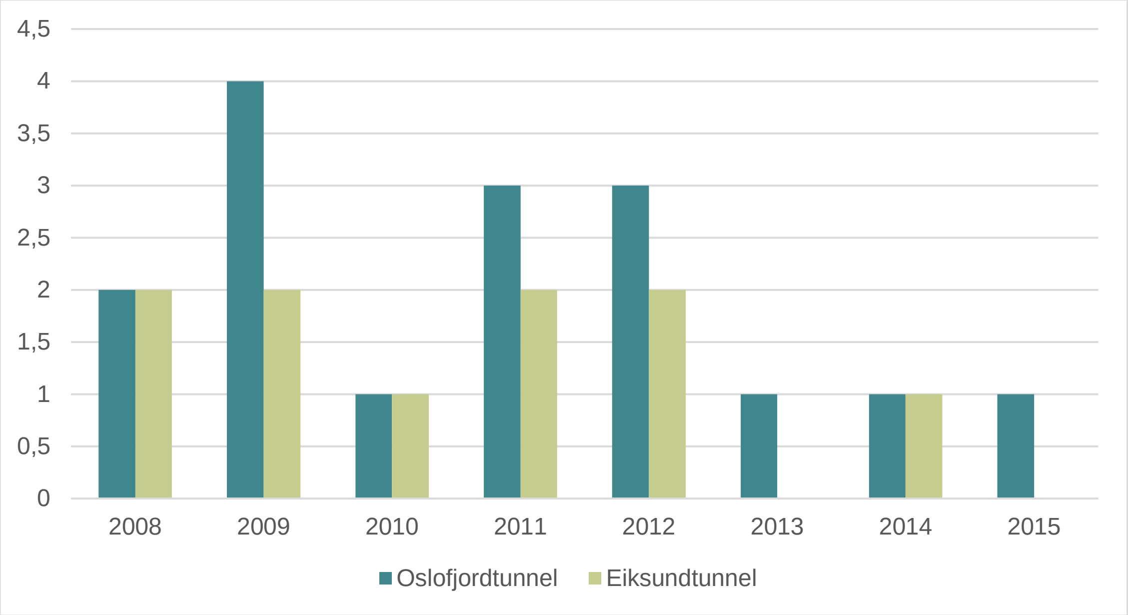

Figure S.3: Annual number of fires and smoke without fire in Oslofjordtunnelen (N = 16) and Eiksundtunnelen (N = 10) from 2008 to 2015.

One of the main objectives of the measures in the Oslofjordtunnel has been to inform drivers of heavy vehicles that they should drive slowly into the tunnel and use a low gear all through the tunnel. For example, signage has been improved with information ("low gear") before and inside the tunnel, the speed limit has been lowered to 70 km/h and section control has been installed in the tunnel. The Oslofjord tunnel has also been closed to heavy vehicles in parts of 2011 and 2012. There has also been a focus on fire prevention in the Eiksundtunnelen after the serious road accident and fire 28.06.2009. For example, section control was introduced in April 2012. We must make the proviso that we look at a small number of events over a limited time period in these two tunnels, so we should exercise caution when it comes to drawing firm conclusions about the development and its causes.

It may, however, be relevant to examine whether lessons from the measures implemented in these two tunnels can be transferred to other road tunnels with high gradient. It is not sufficient to look at the Oslofjordtunnelen alone, but future research can map and systematically evaluate each of the measures in light of experiences from recent years from the Oslofjordtunnelen and findings in international research. Focus should be on what measures we can assume to be most effective and least costly to implement.

The Byfjord tunnel and the Bømlafjord tunnel do not exhibit the same reduction in the number of events as the Oslofjordtunnelen and the Eiksundtunnelen in 2008-2015. These tunnels had a total of 17 events in the period 2008-2011, as compared to 13 in the period 2012-2015. Again we must warn that we should be cautious to draw firm conclusions based on small numbers.

In addition, there are three other subsea tunnels, characterized by relatively high numbers of fires and SWF (a total of 16) in the last survey period (2012-2015): Mastrafjordtunnelen in the western region with 6 fires and SWFs, Valderøytunnelen with 6 fires and SWF, and Hitratunnelen with four fires and SWFs. These had a total of 11 fires and SWFs in the period 2008-2012. Vehicle fire surveys and measures could therefore also focus on these three subsea tunnels.

Potential weaknesses related to data sources and methods

In this report we combine fires and SWFs in the analyses. The reason for it is that we largely assume that the SWFs could develop into fires and that they have largely the same causes and that other traits also are relatively similar. The analyses show that fires and SWFa largely have the same causes, but it must be pointed out that the share of unclear cause is considerable. Another reason why we combine fires and SWFs in the analyzes is that we define SWF as instances of smoke that could become fire (as opposed to what we call "questionable SWF"). However, we cannot be absolutely certain that all SWFs in our database could have developed into fires if they had not been extinguished.

In this study, we rely chiefly on the electronic records of the Norwegian RTC's. This data source lacks a great deal of information about things such as where in the tunnel fires or incidents occurred, damage to vehicles, extinguishing efforts, and they often lack data on the causes of the road tunnel fires. The data on use of fire ventilation is also of varying quality.

We also use data from fire services, and the quality of our data is to some extent a function of their response rate. In the first survey, we had a response rate of 59 % and in the second a 30 % response rate. This is a possible source of weakness for our data.

When all log data from one region had been coded and registered in a spreadsheet, we returned it to the contact persons at the relevant road traffic centre for quality assurance. This is the most important external quality assurance of our data, and it has therefore been a priority in both rounds of data collection. We also sent the data to personnel responsible for tunnel safety and tunnel fire prevention in the regions, but they did not all respond. This is a possible weakness of the data.

In the present study, we have collected and coded new material for the period 2012-2015 in order to merge it with previously collected material for the period 2008-2011. It is crucial that the criteria for inclusion of events are the same in both data collection periods, so that changes cannot be attributed to methodological factors. To ensure that the criteria for registration of fires and characteristics in the most recent survey were the same as in the first mapping, project manager Nævestad has quality assured all reported fires and SWFs in the period 2012-2015. All fires and SWFs for the period 2012-2015 have been reviewed by at least two people, and in cases of doubt, the case has been discussed by at least two and often three project staff.