Tunnel safety, requirements for self-rescue and evacuation - the (mis)use of traffic volume to define the level of safety

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ABSTRACT
The study reported in this paper examines tunnel evacuation as a design parameter for tunnel safety. Average Annual Daily Traffic (AADT) through tunnels is according to regulations important in defining the level of safety. Compared to evacuation in other parts of society, tunnel users are less prepared for events that require immediate evacuation. Evacuations from buildings and air traffic are designed with clearly defined maximum expected person loads, unlike in tunnels where these values are often unknown.

The number of vehicles that must be expected inside a tunnel during a fire incident and the number of vehicles trapped in fire is of major concern. The expected time it takes for evacuees to exit the tunnel on foot has been assessed in this paper, provided that the tunnel user has recognized the urgent need to evacuate. The traffic work or traffic flow (often expressed by AADT) and tunnel length contribute to the number of vehicles inside a tunnel with a fire incident. Other factors, especially the time to close the tunnel after ignition influences the amount of vehicles inside a tunnel and hence, the evacuation times. The comparison of hypothetical tunnels in this paper demonstrates significant variations in the expected evacuation times.

The EU Directive (TSR) sets demanding requirements for individual self-rescue. With current regulations and exceptions in Norwegian regulations (emergency exits should only be established with AADT of 8.000 in long tunnels), the requirements for self-rescue are rarely met. We conclude that Average Annual Daily Traffic should be integrated in an analysis of traffic flow and traffic conditions combined with analysis of actual scenarios rather than relying solely on threshold values to define requirements. Given that AADT represents an average rather than capturing short-term fluctuations or peak conditions, it is insufficient as a direct measure of risk. Instead, risk assessments should prioritize metrics that more accurately reflect real-time exposure, such as Peak ADT, which better represents the maximum number of individuals affected during critical incidents like fires.

Currently, the road users in Norwegian tunnels are left with unrealistic self-rescue demands, which undermines the self-rescue principle, the cooperation principle and the universal design principle.

KEYWORD: Tunnel Safety, Emergency Exit, Average Annual Daily Traffic (AADT)

INTRODUCTION

The EU directive [3] was enacted to establish minimum safety requirements for tunnels within the trans-European road network (TERN). This directive has served as the foundation for the Norwegian Tunnel Safety Regulations (TSR) [1]. This paper examines the prerequisites for the requirements concerning the self-rescue assumption, the establishment of escape routes from tunnels in accordance with the directive, as well as the adaptations made in the Norwegian regulations. The introductory considerations of the EU directive, point 11, state: “Safety measures should enable individuals involved in incidents to rescue themselves, allow road users to take immediate action to prevent more serious consequences, ensure that emergency services can operate effectively, and protect the environment while limiting material damage.”

The Tunnel Safety Regulations require the inclusion of emergency exits for tunnels with an Average Annual Daily Traffic (AADT) exceeding 4.000 vehicles. Additionally, if other risk factors are critical, establishment of emergency exits may be needed. This could be particularly relevant in cases where the tunnel slope exceeds 3%. According to § 8 of the Tunnel Safety Regulations, the Norwegian Public Roads Directorate (NPRD) is given the authority to make exceptions to the emergency exit requirement for tunnels shorter than 10 km and with an AADT less than 8.000 vehicles. This exception is contingent upon a risk analysis demonstrating that equivalent safety or safer system can be achieved through alternative measures.

This paper has analyzed the following research questions:

- *How do Norwegian tunnel owners ensure that the self-rescue requirements stated in the introductory considerations of the EU directive, pt. 11, are fulfilled through the Tunnel Safety Regulations?*
- *How does the use of AADT justify self-rescue requirements as the governing parameter for the establishment of emergency exits?*

Emergency exits from inside tunnels are rarely established in Norway. Primarily, this is undertaken when tunnels with two tubes are constructed, wherein escape is facilitated by cross-connections to the opposite tunnel tube. The motivation behind this study is to explore the reasons behind the limited establishment of escape tunnels in Norway and to analyze the implications of traffic volume being the sole parameter utilized as the basis for this requirement.

EVACUATION FROM TUNNELS IN THE EVENT OF FIRE

Current Methods for Ensuring Safe Evacuation

Experts agree that the evacuation of tunnels during a fire can be complex. There is often an unknown number of individuals within the tunnel, each possessing varying levels of knowledge regarding evacuation procedures. The outcome of an incident will depend on numerous factors, which may vary between different tunnels and events. Such factors include: the length of the tunnel, the tunnel profile, fuel composition, dynamics of the fire, ventilation systems, detection and monitoring, tunnel traffic management, communication with road users, closing barriers at the tunnel entrances, niches to turn around vehicles, the competence of individuals regarding evacuation, occupancy levels, etc.

One of the most critical factors to clarify is: "How many individuals are present in the tunnel during an event that necessitates evacuation?" This can be referred to as occupancy levels, and it should guide the selection of most safety measures within the tunnel. To ensure that the implemented evacuation measures correspond with the risks posed by the expected occupancy, it is currently facilitated by utilizing the tunnel's Average Annual Daily Traffic (AADT).

What is AADT and How Does It Affect Tunnel Safety Levels?

According to the Norwegian Public Roads Administration (NPRA), AADT is defined as follows: "The total number of vehicles, in both directions, that pass a given point on a road over the course of one year, divided by 365." It is a measure based on past observations, an average which does not say anything about the distribution, the variation over the year, seasons, weeks and days. In other words, AADT alone cannot indicate how many individuals are present in a specific tunnel during an incident. Number of vehicles and tunnel-users must be predicted, with inherent uncertainties as well as identifying the assumption of time horizon as basis for the prediction. AADT becomes the presented mean of a distribution rarely described by the risk analysts. To account for increases in traffic, hazardous traffic conditions, and seasonal variations, AADT must be analyzed more closely in each project. Examples of this include the following:

- AADT forecasts for 10 to 30 years into the future are used for capacity planning.
- If proportion of heavier vehicles in the AADT exceeds 15%, AADT must be risk-adjusted/increased.
- If summer daily traffic (SDT) during June, July, and August is significantly higher than the annual average, the AADT must be risk-adjusted/increased.

Thus, AADT is not a static value, and there are numerous uncertainties associated with AADT predictions. It is essential to understand the underlying historical data, the precision of measurement tools, and what premises that are laid down for the prediction of future traffic work. Furthermore, the connection between number of vehicles/traffic users and the performance of the self-rescue system also contains huge uncertainties.

What Does AADT Mean for the Selection of Safety Measures?

Both the EU directive (Tunnel Safety Regulations) and the NPRA's Handbook N500 [5] base safety requirements on AADT. Both documents have the status as a formal regulation. These regulations stipulate safety measures and tunnel designs based on the tunnel's length and AADT. However, the traditional approach regarding tunnel fire rescue and evacuation seem to prevail, it is in general sufficient with evacuation through tunnel entrances.

The uncertainties associated with the use of AADT result in variability regarding how many individuals may be considered present in a tunnel during a fire incident and whether the safety measures have been designed for the specific event. It would be prudent for the risk analysis, as stipulated in §10 of the TSR, to be used as an active tool for analyzing how AADT impacts risk. Additionally, the provisions in Appendix I, pts. 1.1.1 and 1.1.2 of the regulations must be considered, ensuring that the established safety measures are based on a systematic evaluation of all aspects of the system.

Several parameters in 1.1.2 are affected to varying degrees by the segment or tunnel's AADT. By analyzing AADT in a more nuanced manner for each individual tunnel, it becomes possible to identify risks associated with AADT beyond merely constructing facilities based on the frequency of expected incidents. For instance, ferry traffic on each side of a tunnel may lead to significant fluctuations in traffic volumes during certain times of the day, which is not necessarily reflected in the statistics for maximum hourly traffic. If there is a ferry arriving once an hour, most of the traffic may occur within a 15-minute window rather than being evenly distributed over a full hour. The Byfjord tunnel is close to a ferry connection. Consequently, the number of vehicles in the tunnel during an incident could far exceed what the AADT suggests as an average. This exemplifies why AADT may not accurately represent the risk within the tunnel. The scenario highlighted could also be typical for an undersea tunnel, where the observed number of fire occurrences is much higher than tunnels onshore, mostly due to the combination of long tunnels and steep slopes.

There exists an established practice in Norway of not building escape routes before AADT exceeds 8.000, even though this should be evaluated on a case-by-case basis according to the regulations.

Self-Rescue with and without Escape Routes

Self-rescue means that each road user must ensure their own safety, either by using their vehicle, evacuating on foot, or receiving assistance from other motorists. Most tunnels in Norway have longitudinal ventilation, which creates a smoke-free side and a smoke-affected side during a fire. Consequently, the conditions for self-rescue can vary significantly depending on which side of the fire a person is located.

If evacuation on foot is necessary, there is a substantial difference between evacuating a tunnel with escape routes and one without. The TSR mandate a maximum distance of 500 meters between escape routes, while in Manual N500 its a maximum of 250 meters (between cross-connections in dual tube tunnels). In the case of a long single tube tunnel (up to 10 km) without emergency exits, the distance to evacuate may extend several kilometers. Experiences from tunnel fires in Norway, such as those in the Gudvangatunnel [11, 12, 14] and the Oslofjord Tunnel [10, 13], demonstrate that self-rescue was complicated and that individuals were trapped in smoke. In other societal sectors this is approached differently:

Buildings. Evacuation requirements are defined according to the Regulations on Technical Requirements for Construction Works, TEK 17 [2], along with the accompanying guidelines, VTEK 17 [15]. A standard assumption is made of 1 cm exit width per person, with the dimensioning scenario based on the incident with the highest number of occupants present simultaneously. The maximum number of individuals anticipated to be present is thus known in advance. Based on this, evacuation plans and instructions are developed to ensure that individuals within the building are informed about evacuation procedures. In all public and occupational buildings, there are designated individuals tasked with ensuring that the evacuation can occur safely and efficiently. Evacuation plans are typically posted at escape routes and within hotel rooms, among other locations.

Passenger Aircraft. For the evacuation of an aircraft, specific requirements regarding the number and size of emergency exits are established based on the aircraft's passenger capacity. Design requirements are rigorously regulated by national and international standards. The worst-case scenario, with the maximum number of occupants known in advance, guides the requirements for ensuring safe evacuation. Additionally, crew members on all flights are responsible for giving passengers information, as well as managing situations that necessitate evacuation. Information about safety and evacuation procedures is available at each seat.

Summary. Evacuation systems from other constructions than tunnels are based on the scenario in which the maximum allowable number of individuals is present. Also, more information about safety and evacuation is provided to users of buildings and aircrafts than to users of tunnels. Lack of acceptance criteria and dimensioning assumptions for tunnels results in uncertainty regarding the expected number of individuals who may need to evacuate during a given incident. The self-rescue principle requires individuals to take proactive measures to secure their own safety, but the tunnel users are not provided with information and practical advice. There exist many Norwegian tunnels that will engulf tunnel users in smoke in case of fire inside.

METHOD

The following documents has been analyzed:

- Tunnel Safety Directive [3]
- The Norwegian Tunnel Safety Regulations [1]
- Handbook N500-2024 Road Tunnels, including previous versions [5]
- Guidelines for Risk Analyses of Road Tunnels, TS 2007:11 [7]
- Guideline V721 Risk Assessment of Road Traffic Systems [4]
- SINTEF Risk Analysis, AADT 4.000/8.000 [6]

The document analysis shows that there is limited justification for the central role of AADT in the safety management of tunnels and how the threshold values are established.

Analysis of safety in existing tunnels and three hypothetical tunnels

Two existing tunnels were chosen for examination, both without longitudinal escape routes. Traffic data from several years is available for both tunnels, the Byfjord Tunnel in the outskirt of Stavanger and the Oslofjord Tunnel south of Oslo. Both tunnels are subsea with steep slopes. The focus of the analysis has been on examining AADTs and its development in relation to the requirements or needs for emergency exits. The study includes 3 hypothetical tunnels to study variations in safety levels using the current regulation.

Variations in safety levels in tunnels utilizing current regulations

The purpose of the TSR is described in §1; to ensure the lowest permissible safety level for tunnel-users by mandating the prevention of critical incidents that could endanger human lives, the environment and tunnel infrastructure, and to provide protection in the event of accidents. So, what variations are considered acceptable when using the current criteria for safety management in tunnels? The outcome of an incident may be determined by several parameters, including:

- Length of the tunnel
- Availability of emergency exits or rescue rooms
- Gradient/vertical curvature of the tunnel
- Ventilation solutions
- Alarm systems and monitoring
- Barriers to close tunnel
- The number of individuals present in the tunnel at the time of the incident
- Possibilities for turning vehicles around in the tunnel
- Manual firefighting capabilities
- Emergency response times

To narrow and ease the analysis, the tunnel's gradient and profile were not taken into consideration, allowing the assumption that the probability of a fire per vehicle per km remains constant. It is assumed that the tunnels are equipped with longitudinal ventilation. Requirements for emergency exits are based on scenarios with an AADT exceeding 8.000. Requirements for Automatic Incident Detection/Incident Traffic Vision (AID/ITV) are based on the specifications in N500. The analysis will focus on the following parameters:

- Length of the tunnel
- Traffic volume (AADT), with further assessments of occupancy levels
- Availability of emergency exits
- Alarm systems and monitoring
- Barriers to close off tunnel entrances

The analysis examines variations in measures and expected outcomes resulting from these factors. It focuses on the number of vehicles expected to be in the tunnels during an incident, which will have implications for how far the users will need to travel or walk to reach the exit.

RESULTS

Analysis of safety based on AADT in existing tunnels

This chapter provides an analysis of the safety measures established in the Byfjord Tunnel and the Oslofjord Tunnel in relation to the development of AADT over time.

<u>Description of the Byfjord Tunnel</u>

The Byfjord Tunnel is part of the E39 Rennfast connection, which opened in 1992. The bi-directional tunnel is 5.875 meters long and has a maximum gradient of 8%. The tunnel profile is T11.5. It contains three lanes and has a speed limit of 80 km/h. There are speed cameras in both directions (average speed in the northern lane and point camera in southern lane). Safety measures include:

- Emergency niches and niches to turn around vehicles
- Emergency stations: 57 in total (approximately every 100 meters)
- Barriers for tunnel closure in the event of an incident
- Video surveillance (ITV) and Automatic Incident Detection (AID)
- Emergency lighting

The tunnel has longitudinal ventilation, which is typical for tunnels in the Norwegian road network.

On www.trafikkdata.no, the NPRA website, there is a vehicle counting point located at Sokn, north of the tunnel. This counting point has only been operational since 2006. Detailed data from 1992 to 2006 is not readily available. However, an article published in Stavanger Aftenblad (newspaper) on June 18, 2012 [19], indicated that the AADT in 1992 was approximately 4.000. There has been a steady increase in AADT from 2006 to 2023. In 2023 it was 11.313, following a constant upward trend since the initial opening. The tunnel experiences steady traffic throughout the year, with little seasonal variation. However, the highest daily traffic recorded was 16.275 vehicles on June 23, 2023. To further investigate peak loads during worst-case scenarios, data on maximum hourly traffic in 2023 was also reviewed, with a peak of 1.676 vehicles recorded in one hour. The tunnel is connected with a ferry terminal in the north (approx. 12 km from the north entrance of the tunnel), resulting in fluctuations in the traffic pattern.

Description of the Oslofjord Tunnel

The Oslofjord Tunnel opened in 2000. It is 7.306 meters long and has a maximum gradient of 7%. The tunnel profile is T11. The bi-directional tunnel has three lanes and a speed limit of 70 km/h. Notable safety measures include:

- Emergency niches and niches to turn around vehicles
- Emergency stations: approximately every 250 meters, with fire cabinets located between emergency stations
- Evacuation rooms/rescue rooms: distances between rooms range from 150 to 475 meters. One location has a distance of 475 m, and another has 350 m; the rest are 250 m or shorter.
- Emergency exit: Approximately 2 km from the Drammen portal, leading directly to safety
- Barriers for tunnel closure in the event of an incident
- AID in traffic rooms and evacuation rooms, along with ITV in the escape tunnel
- Emergency lighting

On www.trafikkdata.no, there is a vehicle counting point inside the tunnel; however, data is missing for the years 2014 to 2016, and it was closed in 2017. Another counting point is located just outside the tunnel on the eastern side and has been operational since 2000. There has been a steady increase in AADT from 2000 to 2023, rising from 3.419 to 10.860. The tunnel maintains a consistent traffic flow throughout the year, with slight seasonal variations. The variations are larger than those observed for the Byfjord Tunnel but not substantial enough to warrant emphasis in further analyses. The highest recorded daily traffic was 15.748 vehicles on May 26, 2023. To examine peak loads during worst-case scenarios, data regarding maximum hourly traffic in 2023 has also been collected, with a maximum of 1.529 vehicles recorded in one hour.

Analysis of AADT and safety level - assumptions

It is assumed that the requirements outlined in the TSR apply to both tunnels, and reference is made to §2 and §14 of the regulations, which state that tunnels not meeting the criteria should be upgraded and approved by the NPRD. TSR further states that "for existing tunnels longer than 1.000 meters with a traffic volume exceeding 2.000 vehicles per lane, it must be assessed whether it is feasible and effective to create new emergency exits." In Norway, it is understood through §8 and prevailing practices that this threshold is at 4.000 vehicles per lane, corresponding to an AADT of 8.000.

The regulations direct that emergency exits should be established when AADT exceeds 8.000. At the same time, it must be evaluated whether such measures are feasible and effective. While the feasibility will not be challenged in this study, it is evident that establishing emergency exits would be beneficial in the event of a fire, bearing in mind the obvious threat of individuals being trapped by fire and smoke within the tunnel.

Analysis of AADT and safety level – Byfjord Tunnel

The TSR came into force in 2007, and according to www.trafikkdata.no, the AADT exceeded the 8.000 threshold since 2010. According to §14, renovations for tunnels were required to be completed by April 30, 2014, with an option to extend the deadline by five years. Since the tunnel has not established escape routes, it must be concluded that it has not been considered feasible and effective.

This is despite the traffic volume being 2.83 times higher than the AADT threshold in the EU directive and 1.4 times higher than the AADT threshold in §8 of the regulations.

It is anticipated that traffic through the Rennfast connection, and subsequently through the Byfjord Tunnel, will decrease significantly when the Rogfast project opens in 2033, as E39 will no longer pass through Rennfast. The extent of the reduction in traffic through the Byfjord Tunnel is currently unknown, but a substantial decrease is expected. The AADT for the Byfjord Tunnel heading toward 2033 is not known, but applying an increase similar to the previous decade (2013-2023) from 9.270 to 11.313 (approximately 22%) would result in an expected AADT of 13.802. According to the E39 Rogfast Risk and Vulnerability Analysis from 2012 [17], AADT is predicted to be 13.000 20 years after opening.

Analysis of AADT and safety level – Oslofjord Tunnel

According to www.trafikkdata.no, the AADT surpassed the 8.000 threshold in 2016. There is access to an escape tunnel located approximately 2 km from the Drammen portal. However, this escape route has only one exit from the tunnel, resulting in long distances compared to longitudinal escape tunnels as required by the TSR, which stipulate a maximum of 500 meters between emergency exits. The escape tunnel contributes to the performance of the evacuation system and provides the fire services with an alternative access route, but it does not meet the regulatory requirements. Following the fire in in 2011 [10], rescue rooms were constructed in 2012, providing escape options to temporary safe locations. These rescue rooms conflict with the EU directive and TSR requirements. This analysis does not assess the safety of the rescue rooms, but it can be concluded that these measures were established to enhance safety.

In 2023, the AADT was recorded at 10.860, which is 2.72 times higher than the AADT limit established in the EU directive and 1.36 times higher than the AADT limit in §8 of the Tunnel Safety Regulations. There are plans to establish an additional tunnel section through the E134 Oslofjord Connection – Construction Phase 2. The completion date is not known but can be assumed to be around 2032. The AADT for the Oslofjord Tunnel heading toward 2032 is also unknown, but a similar increase to the previous nine-year period (2014-2023) from 7.459 to 10.860 (approximately 46%) would yield an expected AADT of 15.856.

Byfjord and Oslofjord Tunnels – AADT as a basis for safety management

The two tunnels exhibit a somewhat similar trend in traffic volume and, aside from their lengths, are constructed with comparable specifications in terms of gradient and number of lanes. Furthermore, both tunnels must comply with the same requirements for emergency exits as per the TSR. The AADT for both tunnels indicates that, unless it can be demonstrated that establishing emergency exits is not feasible and effective, such exits should have been established for both tunnels. For the Byfjord Tunnel, the AADT exceeded 8.000 in 2010, and for the Oslofjord Tunnel, this threshold was exceeded in 2016. With the anticipated opening of Rogfast in 2033, leading to a subsequent expected reduction in AADT, the Byfjord Tunnel has had 23 years with an AADT greater than 8.000 without any emergency exits being established. For the Oslofjord Tunnel, the establishment of emergency exits is expected to occur with the addition of a new tunnel section, assumed to be completed by 2032. Thus, the Oslofjord Tunnel would have had 16 years with an AADT exceeding 8.000.

Both tunnels have undergone extensive upgrades. Assuming that the rescue rooms sufficiently protect individuals from fire and smoke in the event of a fire, there is a significant difference in the self-rescue abilities between the two tunnels. Additionally, the escape tunnel in the Oslofjord Tunnel provides a positive contribution to evacuation options, along with facilitating the fire service's access capabilities. Nevertheless, questions need to be raised why it has been accepted not to establish emergency exits, especially for the Byfjord Tunnel, and why there are substantial differences in the implemented measures in the two tunnels. Furthermore, it should be noted that the Byfjord Tunnel may experience larger accumulations of traffic due to the ferry connection between Arsvågen and Mortavika. Whether this effect is captured in the maximum hourly traffic is uncertain and has not been further studied in this paper. According to TØI Report 1948/2023 [8], 112 out of 226 fires and fire incidents in tunnels occurred in tunnels with steep gradients, with 23 of the fires in the Byfjord Tunnel and 40 in the Oslofjord Tunnel.

Variations in safety levels in tunnels under current regulations
This chapter presents an analysis of the variations in safety levels that can be expected under current regulations, taking three hypothetical tunnels into considerations. The highest hourly traffic is determined to be 14.8%, which aligns with the proportion observed in the Byfjord Tunnel in 2023. The speed limit for all tunnels is set at 80 km/h, except for the Oslofjord Tunnel, which has a speed limit of 70 km/h. For each tunnel, safety equipment is defined on actual conditions for the existing tunnels or in accordance with N500 for the hypothetical tunnels. Based on this, the analysis contain:

- Differences in self-rescue capabilities (with or without emergency exits).
- Expected number of vehicles during an incident.
- Anticipated number of vehicles that would be caught downstream and upstream of the fire, and which would need to evacuate either by vehicle or on foot in smoke.
- Estimated time required for evacuation on foot (based on the stopping point in the middle of the tunnel or worst-case scenarios between escape alternatives).

The analysis assesses how variations in AADT influence safety levels and how this, in turn, affects the drivers' ability to perform self-rescue. The expected number of vehicles in the tunnel during an incident will be statistically calculated based on maximum hourly traffic and speed/travel time. Additionally, the time to close the tunnel is crucial for the outcome of the incident response. For comparison, in tunnels equipped with ITV/AID and barriers, the closing time will be set to 60 seconds. In tunnels without ITV/AID, but with barriers or traffic lights for tunnel closure, this time will vary significantly and depend on how long it takes for road users to notify the Traffic Control Center to initiate closure. This will also depend on how many people are present in the tunnel, how individuals assess the situation, the speed of fire progression, etc. For the purpose of comparison, the time to close the tunnel will be set to 5 minutes (300 seconds). This is just an assumption since no data has been collected for this and its likely to be large variations between events.

It is assumed that the same number of vehicles travel in each direction in the tunnel during a fire incident. It is also assumed that the ventilation system has a fixed direction which activates in the event of a fire. The analysis does not calculate the impact of ventilation on the evacuation process other than noting that it will create an upstream (smoke-free) and a downstream (smoke-filled) zone, which will subsequently affect drivers' opportunities for self-rescue.

The size of the fire is not explicitly defined in the analysis, but it is assumed to involve a fire/accident that blocks both lanes of traffic. It is further assumed that vehicles that have passed the fire, regardless of whether they are upstream or downstream, will drive out of the tunnel. The figure below illustrates an expected normal distribution scenario for defining how many individuals would be blocked by the fire/accident. In the analysis this is based on maximum hourly traffic, length of the tunnel and travel speed. Consequently, these individuals would need to either turn their vehicles around or evacuate on foot, leading to different outcomes depending on whether they are positioned upstream or downstream of the fire. Safety measures such as emergency niches are not illustrated, as they vary among the different tunnels.

Walking speed is set to 1.4 m/s [16] for comparison between the tunnels, but it will vary and does not consider evacuation in smoke or the evacuation of wheelchair users, elderly persons, etc. Regarding evacuation time on foot, a simplification has been made by assuming that evacuation starts without accounting for reaction and decision-making time. This results in an unrealistically short evacuation time; in reality, the total time required for evacuation will be longer. Evacuation time on foot is only used for comparison between the various tunnels, and the method is therefore considered relevant. Calculating reaction and decision-making time will represent large uncertainties and will be complex to calculate.

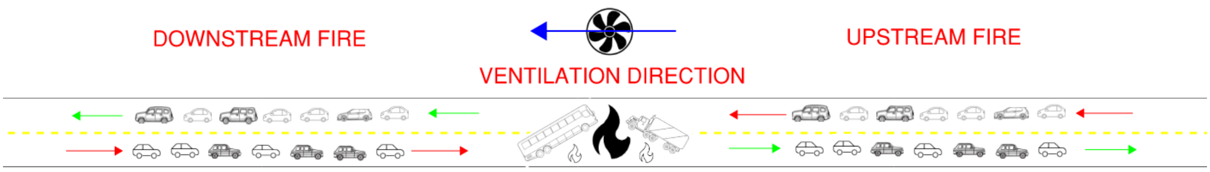

Figure 1 *Vehicles blocked in the tunnel by fire/accident. Vehicles traveling in the direction of the green arrow are assumed not to be involved in the accident, while vehicles traveling in the direction of the red arrow are blocked by the accident/fire and tunnel users must either turn around or evacuate on foot.*

<u>Tunnel Analysis – Byfjord Tunnel</u>

Table 1 *Byfjord tunnel*

AADT	11.313	Vehicles/sec	0,47
Length (m)	5.875	Time from fire start to closure	60
Tunnel Class (according to current regulations)	D	Total vehicles at fire start	123
Emergency exits	No	Total vehicles between fire start and closure	28
AID og ITV	Yes	Total vehicles in tunnel at fire	151
Barriers to close tunnel	Yes	Total vehicles downstream fire – blocked by fire	45
Maximum hourly traffic (vehicles/hour)	1.676	Total vehicles downstream fire – passed the fire	31
Speed (m/s)	22,2	Total vehicles upstream fire – blocked by fire	45
Travel time	265	Total vehicles upstream fire – passed the fire	31

The analysis is based on the current situation. It shows that at the start of the fire, there will be 123 vehicles in the tunnel, and after 60 seconds before closure, an additional 28 will have entered the tunnel. The latter are all expected to become trapped in the tunnel due to the fire/accident. This implies that there will be 45 vehicles on either side of the fire that must either turn around and exit, get assistance from other motorists, or evacuate on foot. The expected evacuation time on foot, assuming one is located at the center of the tunnel and moving at a walking speed of 1.4 m/s, will be approximately 35 minutes. The walking speed will be dramatically reduced if evacuating in smoke.

<u>Tunnel Analysis – Oslofjord Tunnel</u>

Table 2 *Oslofjord tunnel*

AADT	10.860	Vehicles/sec	0,42
Length (m)	7.306	Time from fire start to closure	60
Tunnel Class (according to current regulations)	D	Total vehicles at fire start	160
Emergency exits	1 + rescue rooms	Total vehicles between fire start and closure	25
AID og ITV	Yes	Total vehicles in tunnel at fire	185
Barriers to close tunnel	Yes	Total vehicles downstream fire – blocked by fire	53
Maximum hourly traffic (vehicles/hour)	1.529	Total vehicles downstream fire – passed the fire	40
Speed (m/s)	19,4	Total vehicles upstream fire – blocked by fire	53
Travel time	377	Total vehicles upstream fire – passed the fire	40

The Oslofjord Tunnel is equipped with an escape route and rescue rooms, with distances ranging from 150 to 475 meters. This analysis is based on the current situation. It shows that at the start of the fire, there will be 160 vehicles in the tunnel, and after 60 seconds before closure, an additional 25 vehicles will have entered the tunnel. The latter are all expected to become trapped in the tunnel due to the fire/accident.

This implies that there will be 53 vehicles on either side of the fire that must either turn around and exit, get assistance from other motorists, or evacuate on foot. The walking time to the nearest rescue room and to the emergency exit is calculated. The maximum distance between two rescue rooms is considered to be 475 meters. Given that the emergency exit is approximately 2 km from the Drammen portal, the distance between the escape route and the Drøbak portal is established (7.306 m – 2.000 m

= 5.306 m / 2 = 2.653 m). The expected evacuation time on foot to the nearest rescue room, based on a walking speed of 1.4 m/s, will be approximately 3 minutes, and the expected evacuation time to the emergency exit will be around 31.5 minutes. The expected time to fully exit the tunnel will be approximately 43.5 minutes. The walking speed will be dramatically reduced if evacuating in smoke.

Tunnel Analysis 1 – Tunnel Class B, Length 4.990 meters / AADT 3.990

This hypothetical tunnel will have a length of 4.990 meters and an AADT of 3.990. This gives the requirements Tunnel Class C, thus exempting it from AID and ITV requirements. It would be reasonable to install these measures, as the tunnel is marginally shorter than the requirements, but this example is used to illustrate how this can affect the number of vehicles that may be trapped by a fire in the tunnel due to delayed detection and closure.

Table 3 *Tunnel Class B, length 4.990 meter / AADT 3.990*

AADT	3.990	Vehicles/sec	0,16
Length (m)	4.990	Time from fire start to closure	300
Tunnel Class (according to current regulations)	B	Total vehicles at fire start	37
Emergency exits	No	Total vehicles between fire start and closure	49
AID og ITV	No	Total vehicles in tunnel at fire	86
Barriers to close tunnel	Only light signal	Total vehicles downstream fire – blocked by fire	34
Maximum hourly traffic (vehicles/hour)	591	Total vehicles downstream fire – passed the fire	9
Speed (m/s)	22,2	Total vehicles upstream fire – blocked by fire	34
Travel time	225	Total vehicles upstream fire – passed the fire	9

The analysis shows that at the start of the fire, there will be 37 vehicles in the tunnel, and after 300 seconds before closure, an additional 49 vehicles will have entered the tunnel. The latter are all expected to become trapped in the tunnel due to the fire/accident. This implies that there will be 34 vehicles on either side of the fire that must either turn around and exit, get assistance from other motorists, or evacuate on foot. The expected evacuation time on foot, assuming one is located at the center of the tunnel and walking at a speed of 1.4 m/s, will be approximately 29.5 minutes. The walking speed will be dramatically reduced if evacuating in smoke.

Tunnel Analysis 2 – Tunnel Class C, Length 9.990 meters / AADT 7.000

This hypothetical tunnel will have a length of 9.990 meters and an AADT of 7.000. This places it just under the 10 km threshold permitted by N500. Furthermore, the AADT is 1.000 vehicles below the requirement for establishing emergency exits.

Table 4 *Tunnel Class C, length 9.990 meter / AADT 7.000*

AADT	7.000	Vehicles/sec	0,29
Length (m)	9.990	Time from fire start to closure	60
Tunnel Class (according to current regulations)	C	Total vehicles at fire start	130
Emergency exits	No	Total vehicles between fire start and closure	17
AID og ITV	Yes	Total vehicles in tunnel at fire	147
Barriers to close tunnel	Yes	Total vehicles downstream fire – blocked by fire	41
Maximum hourly traffic (vehicles/hour)	1.036	Total vehicles downstream fire – passed the fire	32
Speed (m/s)	22,2	Total vehicles upstream fire – blocked by fire	41
Travel time	450	Total vehicles upstream fire – passed the fire	32

The analysis shows that at the start of the fire, there will be 130 vehicles in the tunnel, and after 60 seconds before closure, an additional 17 vehicles will have entered the tunnel. The latter are all expected to become trapped in the tunnel due to the fire/accident. This means that there will be 41 vehicles on either side of the fire that must either turn around and exit, get assistance from other motorists, or evacuate on foot. The expected evacuation time on foot, assuming one is located at the center of the tunnel and walking at a speed of 1.4 m/s, will be approximately 59.5 minutes. The walking speed will be dramatically reduced if evacuating in smoke.

Tunnel Analysis 3 – Tunnel Class D, Length 5.000 meters / AADT 8.000

This hypothetical tunnel will have a length of 5.000 meters and an AADT of 8.000. This places it exactly at the threshold for establishing emergency exits, as previously described.

Table 5 *Tunnel Class D, length 5.000 meter / AADT 8.000*

AADT	8.000	Vehicles/sec	0,33
Length (m)	5.000	Time from fire start to closure	60
Tunnel Class (according to current regulations)	D	Total vehicles at fire start	74
Emergency exits	Yes	Total vehicles between fire start and closure	20
AID og ITV	Yes	Total vehicles in tunnel at fire	94
Barriers to close tunnel	Yes	Total vehicles downstream fire – blocked by fire	28
Maximum hourly traffic (vehicles/hour)	1.184	Total vehicles downstream fire – passed the fire	19
Speed (m/s)	22,2	Total vehicles upstream fire – blocked by fire	28
Travel time	225	Total vehicles upstream fire – passed the fire	19

This tunnel is equipped with emergency exits. The distance between emergency exits should, according to TSR, be maximum 500 meters. The analysis shows that at the start of the fire, there will be 74 vehicles in the tunnel, and after 60 seconds of closure, an additional 20 vehicles will have entered the tunnel. The latter are all expected to become trapped in the tunnel due to the fire/accident. This means that there will be 28 vehicles on either side of the fire that must either turn around and exit, get assistance from other motorists, or evacuate on foot. When evacuating on foot, the assumption is made that individuals will head towards the nearest escape route. With a maximum distance of 500 meters between escape routes, a distance of 250 meters is assumed if one is located midway between two exits. The expected evacuation time on foot will be approximately 3 minutes.

Comparing the safety of tunnels

It is essential to distinguish between the results of the two existing tunnels and the three hypothetical tunnels due to their different conditions, particularly regarding their construction dates. However, it is interesting to observe the differences in safety levels since all tunnels must meet the requirements outlined in the TSR. To compare the risks in the various tunnels, the table below shows the number of vehicles blocked by fire/accident downstream and upstream of the fire, as well as the expected time for evacuation on foot in cases where individuals are unable to reach a safe or temporary safe location using their own or others' vehicles.

Table 6 *Comparison of analyzed objects*

	AADT	*Length*	*Vehicles in tunnel fire*	*Vehicles blocked upstream fire*	*Vehicles blocked downstream fire*	*Evacuation time on foot**
Byfjord tunnel	11.313	5.875 meters	151	45	45	35 minutes
Oslofjord tunnel	10.860	7.306 meters	185	53	53	3 minutes
Tunnel 1	3.990	4.990 meters	86	34	34	29,5 minutes
Tunnel 2	7.000	9.990 meters	147	41	41	59,5 minutes
Tunnel 3	8.000	5.000 meters	94	28	28	3 minutes

* Evacuation time calculated from the center of the tunnel where individuals evacuate fully and from the midpoint between emergency exits where applicable. For the Oslofjord Tunnel, the distance is considered midway between two rescue rooms involving the longest distance.

The analysis indicates that AADT plays a significant role in defining how many vehicles may become trapped in the tunnel during a fire. The length of the tunnel is also a decisive factor; however, how quickly the tunnel is closed are crucial for reducing the number of vehicles present during a fire.

There are significant differences in walking evacuation times, which is critical when smoke is travelling the same direction. Tunnel 3, which is 5.000 meters long, will be evacuated within approximately 3 minutes, whereas Tunnel 1, at 4.990 meters needs 29.5 minutes. If this tunnel were 10 meters longer, it would be classified as Tunnel Class C, requiring AID and ITS, resulting in a faster closure of the tunnel and a reduction from 68 vehicles to 28 vehicles trapped by the accident. However, this does not impact the requirements for emergency exits with this AADT, nor does it affect evacuation times on foot.

Furthermore, individuals evacuating on foot in the Oslofjord Tunnel would be able to reach a safe location in just 3 minutes, whereas individuals in the Byfjord Tunnel would take approximately 35 minutes. The difference in safety levels regarding self-rescue during a fire for two otherwise similar tunnels is considered substantial. It should be noted that the use of rescue rooms contradicts the requirements of the EU directive. Assuming these rescue rooms are constructed with adequate safety levels, they represent a significant enhancement in self-rescue safety. The quality and effectiveness of the rescue rooms have not been further evaluated in this paper.

There is also substantial discrepancy in the safety levels between Tunnel 2 and Tunnel 3. This illustrates how an increase in AADT from 7.000 to 8.000 require better conditions for self-rescue, even though the tunnel without emergency exits is nearly twice as long and has an estimated evacuation time of close to one hour.

DISCUSSION

The study claims that the use of AADT, as it is currently approached, places greater emphasis on the likelihood of an adverse event occurring rather than on the consequences of such an event.

Safety Levels in Existing Tunnels

The safety levels of the Byfjord Tunnel and the Oslofjord Tunnel have been evaluated based on the information gathered. Comprehensive analyses of the tunnels' safety levels, in accordance with the requirements of §10 of the TSR, have not been carried out in this paper. The intention has been to study the development of AADT in the tunnels and how this has affected safety level requirements, particularly concerning the establishment of emergency exits. The findings show that traffic has largely exceeded the values that require emergency exits as per Appendix I, section 2.3.6 of the TSR (and §8 of the regulations), if it is deemed both feasible and effective to establish them. With the expected completion of the Rogfast project in 2033, the Byfjord Tunnel will have been in operation for 23 years with an AADT greater than 8.000 without any escape routes being established. In comparison, the Oslofjord Tunnel will have been in service for 16 years with an AADT exceeding 8.000, awaiting the completion of a new tunnel section in 2032. The tunnel has one perpendicular emergency tunnel, and rescue rooms. They must be seen as compensatory measures for the establishment of emergency exits, providing protection against the effects of fire and smoke. The two tunnels appear quite similar in terms of safety level when considering length, gradient, and AADT.

Whether past incidents have prompted these differences, or if other underlying factors exist, has not been further studied. Given the number of fires and near-fires between 2008 and 2021 [8] - 23 incidents in the Byfjord Tunnel compared to 40 in the Oslofjord Tunnel, it would seem reasonable that similar measures had been considered for both tunnels. From the outset of the regulatory plans for single-tube tunnels, it is essential to stipulate the conditions under which emergency exits should be established. This could provide greater predictability in safety management and necessitate the allocation of investments for upgrades in a long-term perspective.

Variations in safety levels under current regulations

The results from the analysis of three hypothetical tunnels based on length and AADT indicate significant discrepancies regarding the safety measures required in relation to the expected incident considered. AADT has some influence on the number of vehicles anticipated to be trapped by a fire accident. Moreover, the differences between vehicles being trapped in the three hypothetical tunnels are minor, ranging from 56 vehicles in Tunnel 3, 68 vehicles in Tunnel 1, and 82 vehicles in Tunnel 2. Since emergency exits are established in Tunnel 3, the evacuation time on foot is projected to be only

3 minutes, while the time will be nearly 30 minutes for Tunnel 1 and almost 60 minutes for Tunnel 2. These differences in safety levels are considered to be unreasonable.

Tunnel 1 may be seen as somewhat inappropriately dimensioned since it is at the threshold of requiring the establishment of AID and to be classified as Tunnel Class C. To test variations, the length could be set to 5.000 meters while the AADT is simultaneously decreased to 2.000. In this case, the time to close the tunnel could similarly be set to 60 seconds, as for the others. This, combined with a halving of the traffic volume, would lead to a reduction in the number of vehicles trapped by fire from 68 to 14. This is a significant reduction; however, evacuating those positioned downstream of the fire would still be complex, both by vehicle and on foot, potentially taking around 30 minutes.

Considerations regarding consequences of fire incidents in current regulations

One may question whether the use of AADT focuses too heavily on reducing the probability of an incident occurring. The examples provided indicate that safety management of buildings and air traffic, maximum anticipated occupancy is used, while for tunnels, the expected value (AADT) is employed. So, how are the consequences incorporated into the risk management for tunnels? Does a lower assumed AADT justify low likelihood of fire and subsequently low risk? Analyses indicate that tunnels without emergency exits and without rescue rooms may experience a variation of between 68 and 90 vehicles trapped by a fire accident.

If vehicles located upstream of a fire can evacuate safely to an exit, the various tunnels, including Tunnel 1 with the reduced AADT, would have between 7 and 45 vehicles blocked downstream of the fire. With just 7 vehicles, for example one tourist bus carrying 50 people involved, implying that in the worst-case scenario there could be an incident involving 60-70 people downstream. An incident involving 45 vehicles downstream could lead to far more individuals trapped in the tunnel, presenting the potential for a major disaster under the Major Accident Regulations [18].

It is essential to differentiate between risks associated with traffic safety, which encompass numerous incidents throughout the year, and the rare, critical incidents such as a fire in a tunnel. It is challenging to contend that safety management utilizing AADT is particularly suited to address these situations.

Discussion of research questions

The first research question in the study is described as follows: *How do Norwegian tunnel owners ensure that the self-rescue requirements stated in the introductory considerations of the EU directive, pt. 11, are fulfilled through the Tunnel Safety Regulations?*

It is difficult to assert that the current tunnels, and those constructed under current regulations, will adequately address the self-rescue requirements. This concern arises from the uncertain number of vehicles that may be involved in fires where self-rescue must be considered complicated, especially for those located downstream of a fire. Additionally, the knowledge regarding self-rescue among road users varies significantly. Experiences from incidents, such as the fire in the Gudvanga tunnel, demonstrate that self-rescue can be complex even with a small number of vehicles involved.
If the self-rescue requirement in pt 11 of the EU directive is to be fulfilled, there must be a greater commitment to a practice where the overall safety of tunnels is assessed according to the intention of Appendix I, section 1.1.1 of the TSR, which states: *"Safety measures implemented in a tunnel shall be based on a systematic assessment of all aspects of the system, comprising infrastructure, usage, road users, and vehicles."* Section 1.1.2 further specifies the parameters to be considered. This approach would better tailor the safety levels to the specific risks of each tunnel.

The second research question in the study is described as follows: *How does the use of AADT justify self-rescue requirements as the governing parameter for the establishment of emergency exits?*

As described in the analysis, AADT is a predicted mean value. The associated figures will introduce significant uncertainties regarding future developments and, importantly, how to define a dimensioning scenario based on an annual average. If AADT is to be used appropriately, seasonal adjustments, risk adjustments, and assessments of maximum values for daily and hourly traffic must be performed. This would provide a more solid foundation for evaluating actual scenarios instead of relying solely on average figures to define requirements derived from the AADT thresholds stipulated in the regulations. As shown, the use of AADT can lead to substantial fluctuations in safety measures and overall safety levels.

Recommendations for further work

Self-rescue is complicated in tunnels, and adherence to current regulatory requirements results in highly variable safety level across Norwegian tunnels. Is it acceptable to continue constructing single-tube tunnels without emergency exits, reserving such measures primarily for tunnels with two tubes?

It is recommended to consider alternative approaches for defining when the establishment of escape tunnels is warranted in Norway. A greater emphasis on the provisions outlined in Appendix I, sections 1.1.1 and 1.1.2 of the TSR would facilitate this. In addition, methods for analyzing these parameters within a holistic tunnel safety framework should be explored. This could lead to a change in practice that moves away from strictly defined thresholds and requirements. A careful application of AADT should be integrated into this process, as it remains prerequisite under section 1.1.2 of the TSR. However, it's role should not be weighted too heavily in defining minimum safety levels.

Historically, AADT was likely chosen for its simplicity, availability, ease of standardization across tunnels, and alignment with the regulatory framework. While it provides a convenient, generalized measure, it's reliance on historical data, often infrequently updated, limits its accuracy in reflecting current traffic conditions.

Given that AADT represents an average rather than capturing short-term fluctuations or peak conditions, it is insufficient as a direct measure of risk. Instead, risk assessments should prioritize metrics that more accurately reflect real-time exposure, such as Peak ADT, which better represents the maximum number of individuals affected during critical incidents like fires. This shift would enhance the reliability of safety analyses and ensure that emergency measures, including evacuation planning and emergency exits, are based on actual peak usage rather than historical administrative conventions.

In relation to methods for analyzing tunnel safety, it is also advisable to establish a practice for defining design scenarios for critical incidents and clear acceptance criteria that can be verified through risk analyses.

Typically, emergency exits are only established in single-tube tunnels when the tunnel is extended with another full-size tube. One reason for this could be that the cost of establishing a parallel escape tunnel, given today's requirements (tunnel profile T5.5 according to N500) is too high. It is therefore recommended to investigate whether it is possible to establish emergency exits within the same profile while allowing a narrower escape route. If simpler methods for constructing emergency exits that meet sufficient safety levels can be identified, this may also promote greater utilization of emergency exits through lower costs.

CONCLUSION

It is challenging to justify that self-rescue is adequately addressed in existing and new tunnels in Norway. The difficulty arises from numerous uncertainties concerning the varying assumptions about how many and which individuals are present in the tunnels, where self-rescue in many instances can be complicated. Often, these situations also involve very long distances to evacuate.

Managing safety in tunnels based on AADT, particularly for the purpose of establishing emergency exits, introduces substantial uncertainties and necessitates more detailed analyses than merely utilizing expected values. Furthermore, AADT conveys little about the consequences of incidents requiring self-rescue. It is crucial to distinguish between risks associated with traffic safety, where incidents occur frequently throughout the year, and the rare and critical incidents such as fires in tunnels. AADT is not adequately suited for assessing the risks associated with these critical events. The use of Peak ADT would better represent the maximum individuals affected during a critical event.

Experience demonstrates that both in existing tunnels and in the planning of new tunnels, substantial variations in safety levels for self-rescue during tunnel fires are anticipated. The results indicate significant differences in evacuation distances and evacuation times on foot. The notable disparities in measures between the Oslofjord Tunnel and the Byfjord Tunnel are striking, given that both tunnels are expected to meet the same regulatory requirements and appear to have similar conditions and risk profiles. However, there have been more critical incidents in the Oslofjord Tunnel compared to the Byfjord Tunnel, which may suggest that incident frequency shapes the safety management practices. This approach could result in high-risk tunnels, where the consequences of accidents could be severe, not receiving the necessary safety upgrades due to the absence of critical incidents. The analysis of the hypothetical tunnels also reveals significant differences in safety levels, which is expected since measures are typically triggered at threshold values associated with increased lengths and AADT. Developing methodologies for conducting more comprehensive analyses of tunnel safety concepts may facilitate a more uniform safety level among various tunnels, thereby placing greater emphasis on the requirements outlined in Appendix I, sections 1.1.1 and 1.1.2 of the TSR.

In comparison to evacuation in other areas of society, it is assessed that road users are poorly prepared for potential incidents that may occur. Evacuation from buildings and air traffic are more clearly defined, with maximum expected occupancy, in contrast to road tunnels where such values are often unknown.

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