Myndighet og regelverk
Konstruksjoner
Tunnelgodkjenning
25.04.2025

Statens vegvesen

Studie av nullventilasjon ved tunnelbranner

En litteraturstudie av RISE

STATENS VEGVESENS RAPPORTER Nr. 1054

Silje Drevdal, Statens vegvesen

Statens vegvesens rapporter

NPRA reports
Norwegian Public Roads Administration

Tittel
Studie av nullventilasjon ved tunnelbranner

Undertittel
En litteraturstudie av RISE

Forfatter
Robert H. Mostad, Lei Jiang

Avdeling
Konstruksjoner

Seksjon
Tunnelgodkjenning

Prosjektnummer
24/319455

Rapportnummer
1054

Prosjektleder
Lene Jermstad

Godkjent av
Kristin Rygg Haugland

Emneord
Litteraturstudie, nullventilasjon, fullskala branntester, numeriske simuleringer, selvredning, lange ettløpstunneler

Sammendrag
En litteraturstudie er gjennomført for å øke kunnskap om nullventilasjon ved tunnelbranner. Konseptet innebærer å redusere luftstrømshastigheten aktivt mot null med mekanisk ventilasjon i tunnelen, og å la røyk spre seg til begge sider av brannkilden. Rapporten viser at det er begrensede data fra store branner, informasjon om røyksjikting og gasskonsentrasjoner, samt bruk av strategien over en lengre periode. Strategien er sterkt avhengig av nøyaktige vindhastighetsmålinger, samt rask og nøyaktig viftestyring. Rapporten konkluderer med et behov for fullskala branntester for å øke kunnskapen om bruk i lange ettløpstunneler uten nødutganger.

Title
Study of zero-flow ventilation strategy during tunnel fires

Subtitle
Literature study by RISE

Author
Robert H. Mostad, Lei Jiang

Department
Structures

Section
Tunnel Approval

Project number
24/319455

Report number
1054

Project manager
Lene Jermstad

Approved by
Kristin Rygg Haugland

Key words
Literature study, zero-flow ventilation, full-scale fire tests, numerical simulations, self-rescue, bidirectional tunnel

Summary
A literature study has been conducted to increase knowledge about zero-flow ventilation during tunnel fires. The concept involves actively reducing the airflow speed to zero with mechanical ventilation, allowing smoke to spread to both sides of the fire. There is limited data from large fires, information on smoke layering, gas concentrations, and the effect of using the strategy over a longer period. Accurate air flow measurements and fast and precise fan control is highly important. The report concludes that full-scale testing is needed to increase the knowledge of zero-flow ventilation in long bidirectional tunnels without emergency exits.

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Study of zero-flow ventilation strategy during tunnel fires

PERSON RESPONSIBLE / AUTHOR
Robert H Mostad / Lei Jiang

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PROJECT NO / FILE CODE	DATE	DOCUMENT CLASSIFICATION
0408-25UTV	25.03.2025	K2 Internal

1 Sammendrag

En litteraturstudie har blitt gjennomført for å vurdere muligheten for å anvende konseptet om nullstrømsventilasjon ved tunnelbranner. I nullstrømsventilasjonsstrategien kontrolleres den langsgående luftstrømhastigheten aktivt nær null gjennom hele tunnelen for å la røyk spre seg likt på begge sider av brannkilden. Denne strategien forventes å være egnet for toveis tunneler og enveis tunneler med stor trafikkmengde, hvor tidlig evakuering forventes på begge sider. Strategien har blitt implementert i flere tunneler i Japan, inkludert tunneler av forskjellige lengder, enveis eller toveis, med eller uten nødutganger. Selv om konseptet ser lovende ut i prinsippet, er det begrenset data og erfaringer fra fullskala eksperimenter. Branntester i Kan-etsu-tunnelen og Mino-tunnelen i Japan demonstrerte vellykket anvendelsen for små branner, og noen andre studier ved bruk av numerisk simulering eller risikovurdering bekreftet også effektiviteten av strategien for evakuering. Imidlertid er fullskala data fra store branner, og informasjon om røyksjiktning og gasskonsentrasjoner, begrenset. Denne strategien er dessuten sterkt avhengig av nøyaktige målinger, samt rask og nøyaktig viftestyring. I tunneloperasjoner gjenstår spørsmål som hvor lang tid det tar å etablere nullstrømmen, hvordan ventilasjonsstrømmen vil påvirke allerede eksisterende røykssjiktning ved aktiveringstidspunktet, og hvor lenge tilstanden kan og bør opprettholdes. Det er behov for spesiell vurdering av den norske veitunnelsituasjonen. Norske tunneler er ofte lange og toveis, ofte med en viss helning og med begrensede evakueringsmuligheter sideveis. Det er derfor en rekke ubesvarte spørsmål tilknyttet dette konseptet. For å identifisere de operasjonelle fordelene og begrensningene ved nullstrømsventilasjonsstrategien, anbefales derfor fullskala branntester i Runehamar-tunnelen.

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2 Summary

A literature study was conducted to evaluate the feasibility of applying the concept of zero-flow ventilation during tunnel fires. In the zero-flow ventilation strategy, the longitudinal airflow velocity is actively controlled close to zero throughout the tunnel to allow smoke to propagate equally on both sides of the fire source. This strategy is expected to be suitable for bidirectional tunnels and unidirectional tunnels with heavy congestion, where early evacuation is expected on both sides. The strategy has been implemented in several tunnels in Japan, including tunnels of various lengths, unidirectional or bidirectional, with or without emergency exits. While the concept appears to be promising in principle, full-scale experimental data are limited. Fire tests in the Kan-etsu tunnel and Mino tunnel in Japan successfully demonstrated the application for small fires, and some other studies using numerical simulation or risk assessment also confirmed the effectiveness of the strategy for evacuation. However, full-scale data on large fires, and information on smoke stratification and gas concentrations, are limited. Moreover, this strategy relies heavily on accurate measurements, as well as fast and accurate fan control. In tunnel operations, questions remain such as how long it takes to establish the zero-flow, how will the ventilation flow affect already existing smoke stratification at the time of activation, and how long the condition can be and should be maintained. There is a need for special consideration of the Norwegian road tunnel situation. Norwegian tunnels are often long and bi-directional, sloped with limited evacuation possibilities sideways. Therefore, there are several unanswered questions related to this concept. To identify the operational benefits and limitations of the zero-flow ventilation strategy, full-scale fire tests in the Runehamar tunnel are therefore recommended.

3 Background

Several tunnel projects have recently proposed a ventilation strategy called zero-flow ventilation strategy, i.e., regulating the tunnel ventilation velocity down to about 0 m/s (e.g. ± 0.5 m/s) to maintain good smoke stratification in the tunnel during the early stage of a tunnel fire. The aim is to facilitate tunnel evacuation. The strategy has been assessed in some studies, but the results are inconclusive, and full-scale experimental studies are limited. Statens vegvesen would like to obtain more knowledge about the principles and the consequences this ventilation strategy can have.

4 Literature study

In order to explore if the concept is tested internationally, a literature survey was carried out as a first step in evaluating this concept. For fire emergency longitudinal ventilation in unidirectional tunnels, there are **four generic ventilation strategies** depending on the target velocity [1,2]: **(1)** critical velocity ventilation (~3-4 m/s), **(2)** low-speed ventilation (~1.5 m/s), **(3)** zero-flow ventilation (~0 m/s), and **(4)** shut-down ventilation from higher values. With respect to traffic conditions, different practices are adopted in Japan and in Europe [2]. In Japan, longitudinal velocity is mostly controlled to a velocity lower than critical velocity (~2 m/s) in traffic without congestion and controlled to zero-flow (~0 m/s) in heavy traffic congestion. In some countries in Europe, longitudinal velocity is controlled to critical velocity (~3-4 m/s) in traffic without congestion and controlled to low-speed mode (~1-1.5 m/s) when water spray is activated or when there is a heavy traffic jam.

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For long bidirectional tunnels, longitudinal ventilation strategies in case of fire are more complex since evacuation both upstream and downstream of the fire source needs to be considered. The considered aspects include the limitation of back-layering upstream of the incident, possible destruction of stratification (downstream of the fire), smoke-propagation speed in conjunction with egress speed and dilution of toxic substances / hot gases [3]. General recommendations suggest that the flow velocity should be kept low to maintain stratification, no jet fans should operate in the smoke zone, and airflow reversal due to ventilation should be avoided [4]. In fact, studies show that when the longitudinal velocity is not large, the smoke stratification downstream can still be maintained [5]. Frey et al. [3] found that the ideal airspeed for longitudinal smoke management for bidirectional/congested traffic situations shall be 1.0 m/s. Air velocities lower than 0.5 m/s shall be avoided due to increased concentrations of toxic gases and high temperatures close to the fire. To minimize the number of casualties 20 min after fire onset, Ilg et al. [6] suggested a velocity of 1.0 m/s or 1.5 m/s for tunnels with a 4% gradient. Riess and Bopp [4] found that in a tunnel with bidirectional traffic, it appeared impossible to control all fire scenarios due to several factors strongly influencing smoke propagation, such as traffic, fire location and tunnel length, tunnel inclination, and meteorological pressure difference. For bidirectional tunnels or unidirectional tunnels with congestion that require evacuation on both sides, zero-flow ventilation allows equal smoke propagation in both directions while the overall smoke propagation speed is minimized, which appears to be a promising strategy. In fact, the zero-flow ventilation strategy has been successfully implemented in several tunnels in Japan, with the tunnel length ranging from 0.6 km to 18 km, according to the information provided by Sohatsu Systems Laboratory. The tunnel types include both unidirectional and bidirectional, both with and without emergency exits.

The concept of zero-flow ventilation was explored in early studies in Kan-etsu tunnel by Mizuno et al., both numerically [7] and experimentally [8]. The tunnel studied was 10 926 m long, equipped with longitudinal ventilation with two vertical shafts. The vertical shafts and their fans were shut down during the fire test. Natural wind at 2.5 m/s and 4 m/s was considered. Evacuation speed was assumed to be 1.7 m/s in the smoke density thinner than 0.1 m^{-1} and 1 m/s in the smoke density less than 0.4 m^{-1}. In the numerical work using a one-dimensional convection model [7], three ventilation strategies were studied: shut-down ventilation, blowing a large amount of air in the sections other than at the fire point, and zero-flow ventilation. It was found that shut-down ventilation was not desirable under some conditions when there was airflow induced by cars and natural wind. In contrast, zero-flow ventilation with automatic control worked out well and stable even under a variety of severe conditions. In the experimental work [8], the natural wind with a velocity of 2.5 m/s was simulated by jet fans. Gasoline pool fires and bus fires were studied. However, the experimental data from the bus fires were not discussed. For the pool fire, a 4 m^2 tray was separated into three parts to set the fire with a time delay. Water spray was started 10 min after setting the fire. With zero-flow ventilation applied against the effect of traffic and natural wind, the airflow velocity came down to 1 m/s in 3 min as a result of fan operation and the smoke was confined within about 1000 m of the tunnel, even 20 min after the fire breakout. Dense smoke was observed near the lower part of the tunnel within 300 m from the fire point due to the water spray activation at 10 min after setting fire. In contrast, with shut-down ventilation, the smoke reached 600 m after 4 min and 3000 m after 20 min. Smoke with density 0.4 m^{-1} came down to 1.5 m above the floor level after 10 min in the region between 100 m and 600 m downstream.

Takahashi and Mitani [9] conducted gasoline pool fire tests in the Mino tunnel, a two-way bidirectional tunnel with a length of 5523 m and a cross-sectional area of 80 m^2. The fire pan was 1 m^2, filled with either 10 L or 20 L gasoline. The maximum tunnel gradient was 1.4%. The wind speed inside the tunnel under normal conditions was estimated to be within 3 m/s - 5 m/s, simulated by a jet fan to create flow at 2 m/s or 4 m/s. In case of a fire, zero-flow ventilation was automatically implemented to set the target wind speed at the fire site to zero. In the three cases tested, the wind speed was reduced to zero 2 minutes after the control began and kept for another 5 min. In terms of evacuation, the smoke moved upstream at a relatively high speed of 1.5 m/s, but smoke concentration at human height (1.5 m above the floor) was not problematic.

Tung et al. [2] conducted numerical studies on the smoke behaviour of different ventilation modes in inclined tunnels using the 3D CFD code Fireles [10]. For a 30 MW fire for four longitudinal gradients (0, 2, 4 and 6%), it was found that velocities of both 0 (zero-flow control) and 1 m/s reveal good performance in maintaining the stratification of smoke in the first 10 min, but it was difficult to distinguish which ventilation mode showed better performance. It was not recommended that the emergency response be operated for more than 10 min or 15 min with either airflow velocity, due to the diffusion of smoke and the increase in CO concentration both upstream and downstream, as shown in Figure 1. Note that in the study, zero-flow ventilation was imposed when the fire was started; the situation could be different if the smoke had already spread from the fire when the zero-flow ventilation started, which was more realistic in relation to what most conditions require.

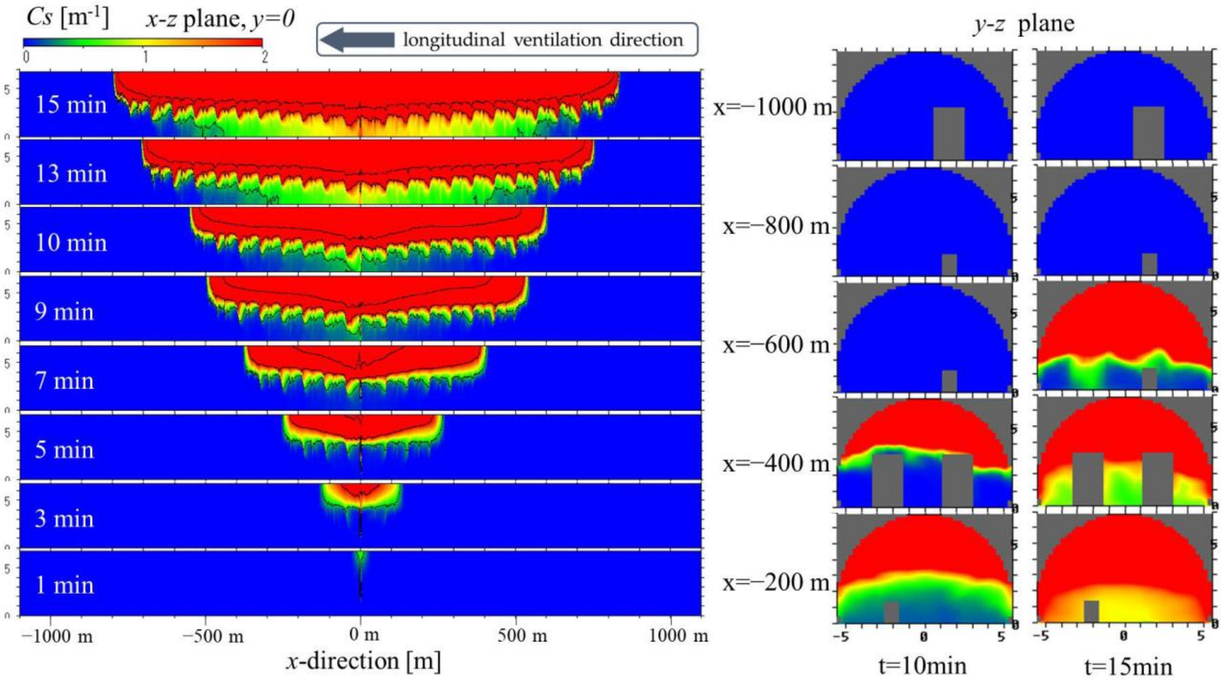

Figure 1. Smoke distribution (Cs, smoke density) with zero-flow ventilation, adapted from Tung et al. [2].

Nakahori et al. [11] conducted a risk assessment of the zero-flow ventilation strategy for fires in bidirectional tunnels with longitudinal ventilation. In the deterministic, scenario-based approach that was common in Japan, the tunnel considered was 2990 m long with a cross-section of 71 m^2. It was assumed that an accident occurred at -60 s, resulting in a 20 MW fire occurring at 0 s, then the fire was detected at 30 s, and emergency ventilation started immediately. The natural airflow was 2 m/s. In the probabilistic process developed in Austria, 135 cases were simulated. In one case, a 30 MW fire occurred in the middle of the 2990 m long tunnel. The natural airflow was 1 m/s. In the shut-down strategy, the airflow was dependent on the buoyancy of the hot gases and the flow direction was changed 430 s after fire started.

Overall, it was found that an actively controlled zero-flow response constituted a significantly lower risk strategy than a simpler response by immediately shutting down all fans.

Sturm et al. [12] suggested that the *near zero velocity* philosophy should not be applied, as the local concentrations of toxic gases, as well as the local temperature, would increase considerably. Moreover, any change in tunnel conditions, such as heat release rate, outside wind pressure, etc., would result in unpredictable smoke movement. Nevertheless, this situation is more like ‘shut-down ventilation’ (Strategy 4) rather than zero-flow ventilation (Strategy 3) discussed in this study (see first paragraph of the section for ventilation strategies). For fan activation, it was suggested that any fans in close proximity to the fire zone should not be activated due to the high turbulence introduced by jet fans.

Kume et al. [13] experimentally studied the airflow velocity to control smoke in sloped road tunnels in a 1:18 small-scale tunnel using an air/helium mixture to simulate smoke. Their small scale tunnel fire tests showed that for a simulated 5 MW fire (full-scale) that occurred in a 3% sloped tunnel with dimensions of 9.54 m × 6.12 m (W × H), an ideal longitudinal airflow velocity of 0.5 m/s resulted in nearly symmetric smoke spread to ensure safe evacuation on both sides. Without longitudinal airflow, more smoke spread towards the upper section. With an airflow of 1 m/s, smoke flow increased in the downward direction.

Huang [14] conducted a safety assessment by comparing the zero-flow ventilation and point extraction ventilation in a tunnel fire where there were many vehicles completely stranded. A model-scale tunnel was built with variable slopes at 0%, 2%, 4% and 6%. The fire source studied was 30 MW (full-scale) with smoke generation of 90 g/s. It was found that when the tunnel slope was 2% or less, zero-flow ventilation could maintain smoke stratification for 10 min or more. As the tunnel slope increased, smoke stratification control became more difficult: 7 min for a 4% slope and 5 min for a 6% slope. For point extraction ventilation, smoke could be controlled between the fire source and the smoke extraction opening regardless of the slope.

Beljaars [15] conducted a feasibility study of implementing zero-flow ventilation instead of an evacuation corridor in the Schiphol Kaagbaan tunnel in the Netherlands. A maximum air velocity of 5 m/s due to wind and traffic was considered. The walking speed of evacuating healthy pedestrians was assumed to be 1.6 m/s. Critical parameters included sight distance, temperature and heat radiation. Using CFD simulations, it was found that with the zero-flow ventilation strategy, safe egress was possible in all the designed scenarios. Nevertheless, the strategy was not applied due to the authority decided that the disadvantages of the ‘Evacuation route’ variant (for building an an evacuation corridor) were not large enough to revise the project design to a zero flow ventilation design concept.

Frey et al. [16] compared two risk assessment models on the effect of different longitudinal ventilation strategies during congested or bidirectional traffic. In the Austrian tunnel model (TuRisMo), zero-flow ventilation was found to be favourable, while in the Swiss model, a longitudinal flow velocity of at least 1.5 m/s was found to be the best strategy. It was found that model differences could potentially contribute to the deviating assessment of low longitudinal flow velocities in case of tunnel fires in a congested environment and for the different assessment of egress distances longer than 300 m. The conclusion was that the best longitudinal ventilation strategy in case of a tunnel fire during traffic congestion existed at best only on a case-to-case basis, but not in a general context.

Although full-scale fire tests with zero-flow ventilation are limited, several full-scale tunnel fire tests were conducted, with a brief summary provided in the book ‘Tunnel Fire Dynamics’ by Ingason et al. [17]. In

Memorial tunnel tests conducted in 1993-1995, sensors measuring air velocity, temperature, carbon monoxide (CO), carbon dioxide (CO_2), and total hydrocarbon content (THC) were installed at 12 cross-sections along the tunnel. The fire source was low-sulfur diesel pool fires, and the size ranged from 10 MW to 100 MW. In Runehamar tunnel test in 2003, the fire source was wood and plastic pallets, furniture or paper cartons, to simulate an HGV-trailer mock-up, with peak HRR in the range of 67-202 MW. In Runehamar tunnel test in 2013, the effect of the water suppression system was studied. The fire source was wood pallets, with the fire developed up to 79 MW.

The aim of zero-flow ventilation is to allow the equal spread of smoke and maintain stratification in both directions. For self-evacuation in a long bidirectional tunnel without emergency exits, the evacuation distance and evacuation time can be very long (e.g. several kilometres and up to 40 minutes), and the consequence of zero-flow to limit the smoke spread even after smoke stratification disappears is also of interest. When there is a natural airflow inside a tunnel induced by traffic, slope or external wind conditions, a counterforce is required to reach zero-flow conditions. In applying zero-flow ventilation, the smoke-filled area will be reduced but the smoke concentration in the vicinity of the fire will be higher [16]. Since the jet fan near the fire site is not recommended for operation so as not to destroy smoke stratification, this strategy is not suitable for very short tunnels. When there is no natural airflow inside the tunnel, no counterforce is needed, and the flow is automatically near zero close to the fire source when ventilation is shut down (there is still airflow induced by entrainment, but the difference between the two sides is not expected to be large). However, this situation is susceptible to external condition changes and may not be common in tunnel operations. A study by Węgrzyński et al. [18] showed that airflow inside the tunnel induced by the wind was sufficient to disturb a buoyant thermal plume, and the flow from vehicle drag could usually overcome the flow created by the wind even at a very low traffic intensity.

At the early stage of a tunnel fire, the smoke stratification in the vicinity of the fire can be well maintained. The smoke flows travel along the ceiling on both sides of the fire source, and thus the human height can be free of smoke. However, it has been found that as the distance from the fire source increases, the smoke layer height gradually decreases until it drops to human height when the whole tunnel cross section is full of smoke [19,20], as shown in Figure 2. This critical distance from the fire source has been found to be about 20 to 40 times tunnel height. This indicates that the smoke stratification cannot be maintained all the time. The duration when good smoke stratification exists is a key issue for the zero ventilation strategy. The expectation is that the zero ventilation strategy may only be valid and helpful for evacuation during the early stage of a fire. When smoke stratification disappears after a certain period of time after applying the zero-flow, the gas concentrations close to and far away from the fire shall be measured to determine if evacuation is still possible, where the whole cross-section is filled with smoke but the concentration may not be deadly.

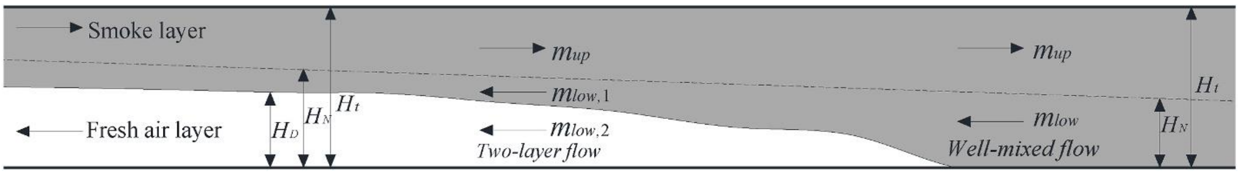

Figure 2. The smoke flow structure in the long tunnel, adapted from Guo et al. [20].

Summary of the literature study

It is found that the literature and experiments on zero-flow ventilation for long bidirectional tunnels are limited, especially for full-scale experiments, and the results are inconclusive [2,16]. In addition to zero-flow ventilation, recommendations for low ventilation flow of 1.0 m/s to 1.5 m/s can also be found [3,6]. As mentioned by Frey et al. [16], the best longitudinal ventilation strategy in case of a tunnel fire during traffic congestion existed at best only on a case-to-case basis, but not in a general context. In Kan-etsu tunnel tests, the fire source was a 4 m^2 gasoline pool fire. In Mino tunnel tests, the fire source was a 1 m^2 gasoline pool fire. In both tests, the HRR was small and estimated to be below 10 MW. Even in numerical simulations [2] or small-scale experiments [14], the studied fire was 30 MW maximum. In the case of a large fire, further study is needed to apply zero-flow ventilation, especially its effect on smoke stratification and smoke concentration.

Another important parameter in applying the strategy is the time needed to establish the flow. Ingason and Romanov [21] conducted FLUENT simulation and theoretical analysis and found that the time to reserve the airflow by fire using a mobile fan (primary flow 37.5 m^3/s) was similar between the case with and without fire (15 MW), but the time was much shorter when there was a blockage inside the tunnel. With a train blockage, the time needed to reverse the airflow was 1 min for Maness tunnel (0.5 km long) and 3 min for Käferberg tunnel (2 km long), while it was 4 min and 10 min for the case without an obstacle. It was also found that the time needed to establish the flow was closely related to the length of the tunnel but not proportional. The effect of tunnel length on the time to establish zero-flow still needs further study. Jiang and Ingason [22] used a mobile fan (primary flow 30.5 m^3/s) to control smoke in Kalldal tunnel (1.1 km long) with a fire size of 1-2.6 MW, and it was found the time to establish flow was 4-5 min. However, data from full-scale experiments using jet fans in a long tunnel with a large fire is still rare regarding the time needed to establish the zero-flow condition.

The third important parameter is the time when the smoke stratification does not exist due to the smoke descent behaviours. After this moment, within the smoke spread regions, the whole tunnel is full of smoke and it makes no sense to make efforts to maintain the smoke stratification. The consequence of limiting the smoke spread with zero-flow over a long period needs to be considered due to higher gas concentrations and higher temperatures expected. It may be recommended that the system be switched to longitudinal ventilation at a certain time. A future project needs to clarify who should determine such activation and under what conditions it is possible. The main focus should be on obtaining conditions beneficial for those who need to evacuate the tunnel, especially in long bidirectional road tunnels without emergency exits.

5 Research interests

While several studies on zero-flow ventilation are available in the literature, and the concept is promising in principle, some important aspects remain unclear. For example, how sensitive is the flow condition development near the fire site, and how practical is it to achieve and keep this condition in real tunnel operations. When starting jet fans to reach zero-flow, the effect of ventilation flow on smoke stratification and smoke concentration is not well documented, especially for the downstream side. Full-scale tests in Kan-etsu tunnel and in Mino tunnel in Japan showed that it took more than 2 min to reach conditions close to zero-flow, but the fire size was small. It is possible that the zero-flow ventilation is suitable for small fires but unsuitable for large fires when there is a large amount of smoke and the zero-flow condition is more difficult to reach.

Due to smoke diffusion and smoke descending, the zero-flow may no longer be suitable when smoke stratification is no longer maintained near the fire source. Experimental data on how long the zero-flow should be kept for a large fire and the consequence of limiting smoke spread over a long period is still missing. As the use of electric vehicles (EVs) is increasing, it is also of interest to investigate a small fire with a long duration to simulate an EV fire that cannot be easily extinguished [23]. Moreover, as the fire size, traffic, and meteorological conditions (e.g. external wind, temperature difference between portals) constantly change, advanced ventilation control systems are usually needed. To study the feasibility of adopting the zero-flow ventilation strategy in Norwegian conditions, full-scale tests in Runehamar tunnel are therefore recommended. With modern reversible jet fans and high-resolution cameras for smoke stratification visualization, questions such as how long it takes to establish the zero-flow, the effect of ventilation flow on smoke stratification, and how long the condition can be and should be maintained will be explored.

6 Test plan proposal

Runehamar tunnel is a two-way asphalted road tunnel with an approximate length of 1520 m, width of about 9 m and height of about 6 m, with a slope of 1% - 3%. The cross-section of the tunnel is about 47 m^2, as shown in Figure 3. The tunnel has an average uphill slope of 0.5% up to about 500 m from the east portal to the west portal, followed by a 200 m long plateau and then a 900 m long downhill section with an average slope of 1 % towards the west portal. Pool fires are planned to be used as the fire source, with a small fire (5 MW) and a large fire (50 MW). Note that pool fires develop relatively fast. In tunnel fire accidents, the fire is expected to develop slower in the early stage.

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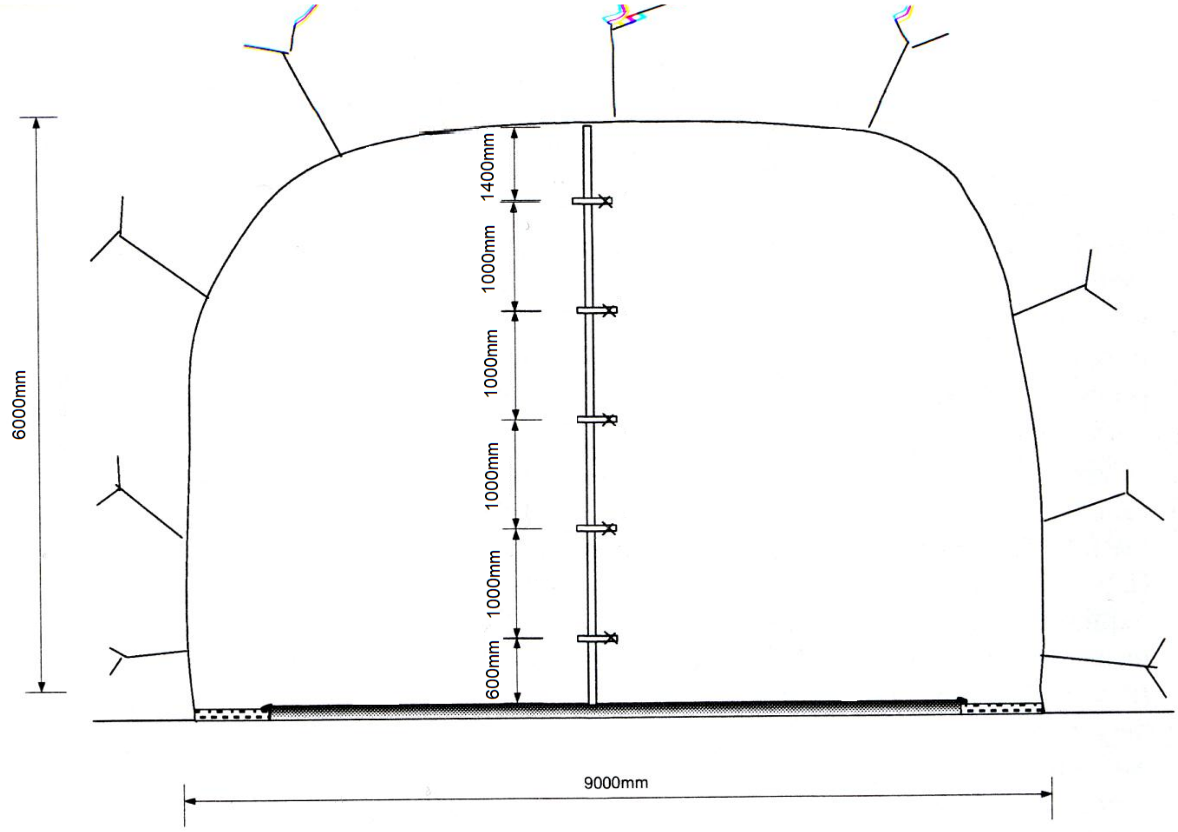

Figure 3. Cross-section of Runehamar tunnel.

Several scenarios are planned, including one pure ventilation test, and two reference cases for a 5 MW fire and two reference cases for a 50 MW fire. The two reference cases are: zero-flow case, and high ventilation case. Alternatively, a low ventilation case of 1.5 m/s can be studied, which is a more commonly used principle in Norway and can be an alternative to zero-flow. They are used as references for comparisons to the zero-flow ventilation strategy. In the tests with zero-flow, the airflow will be actively controlled close to zero, i.e. ±0.5 m/s.

- Scenario 0: ventilation control to zero-flow without fire;
- Scenario 1 (reference case 1 for 5 MW fire): test with a 5 MW fire with zero-flow ventilation during the whole test; *Prior to the test, control the flow to zero and maintain it during the whole test.*
- Scenario 2 (reference case 2 for 5 MW fire): test with a 5 MW fire with high ventilation during the whole test; *Control the flow to a high velocity, e.g., 3-4 m/s, during the whole test.*
- Scenario 3: tests with a 5 MW fire with zero-flow ventilation but with an initially high ventilation velocity; *Prior to the test, keep the flow at a high velocity, simulating longitudinal ventilation, e.g., 3-4 m/s and then rapidly slow down the flow to zero-flow ventilation condition. The zero-flow shall be activated a few minutes after the fire starts to include the time for fire detection and response.*
- Scenario 4 (reference case 1 for 50 MW fire): tests with a 50 MW fire, with zero-flow ventilation during the whole test; *Prior to the test, control the flow to zero and keep it during the whole test.*
- Scenario 5 (reference case 2 for 50 MW fire): test with a 50 MW fire, with high ventilation during the whole test; *Control the flow to a high velocity, e.g., 3-4 m/s, during the whole test.*

- Scenario 6: tests with a 50 MW fire with zero-flow ventilation but with an initially high ventilation velocity; *Prior to the test, keep the flow at a high velocity, simulating longitudinal ventilation, e.g., 3-4 m/s and then rapidly slow down the flow to zero-flow ventilation condition. The zero-flow shall be activated a few minutes after the fire starts to include the time for fire detection and response.*
- Scenario 7: test with 5 MW fire, initially high ventilation, adopt the zero-flow ventilation strategy, but at a given moment (e.g., 10 min) switch it to high ventilation. The moment may be determined by the observation that smoke stratification does not exist any longer, which can be known from cameras. Alternatively, the moment may refer to the time when the smoke travels to the portal where fans are located. The best option would be the shorter time of the above two.
- Scenario 8: test with 50 MW fire, initially high ventilation, adopt the zero-flow ventilation strategy, but at a given moment (e.g., 10 min) switch it to high ventilation. The moment may be determined by the observation that smoke stratification does not exist any longer, which can be known from cameras. Alternatively, the moment may refer to the time when the smoke travels to the portal where fans are located. The best option would be the shorter time of the above two.

Optional scenarios: higher longitudinal ventilation to control backlayering (e.g. 1.5 m/s);

Measurements will include flow velocity, smoke stratification (video), temperature, heat flux, gas concentrations, external wind conditions and pressure in the longitudinal direction. Temperature will be measured upstream and downstream at different elevations and positions. Velocity will be measured at the centreline of the tunnel and half tunnel height and different locations. Frey et al. [3] suggested at least two measurement positions, each one with three independent measurements using ultrasound airspeed measurements. Visibility will be measured at some given locations to quantify the smoke density. Cameras will be used to visualize the smoke spread on both sides of the fire. Gas concentrations will be monitored, since the zero-flow ventilation is expected to cause higher concentrations in the vicinity of the fire. Measurements listed in SOLIT² (Safety of Life in Tunnels) guidelines [24] will serve as a reference, but modifications will be made.

The aim of the full-scale experiments is to study the effectiveness of the zero-flow ventilation strategy in maintaining smoke stratification for early evacuation and the consequence of constraining smoke in the vicinity of the fire for a long period of time, in comparison to the longitudinal ventilation strategy. The operational limitations and adjustments needed for best practices for long bidirectional tunnels without emergency exits will be explored.

Reference

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Verification

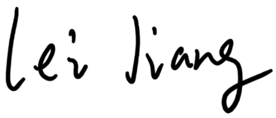
Transaction 09222115557542483963

Document

Memo-tunnel zero-flow
Main document
12 pages
Initiated on 2025-03-25 14:12:40 CET (+0100) by Lei Jiang (LJ)
Finalised on 2025-03-28 08:44:14 CET (+0100)

Signatories

Lei Jiang (LJ)
lei.jiang@risefr.no



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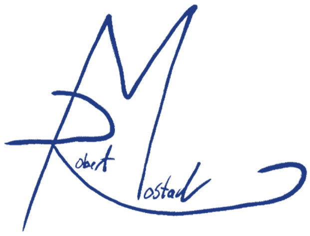
Robert Harley Mostad (RHM)
RISE Fire Research, Norway
robert.mostad@risefr.no



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Statens vegvesen
Pb. 1010 Nordre Ål
2605 Lillehammer

Tlf: (+47) 22 07 30 00

firmapost@vegvesen.no

ISSN: 1893-1162

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