Influence of ventilation on road tunnel fires with and without water-based suppression systems

Ying Zhen Li, Haukur Ingason

Fire Research
SP Report 2016:36
Influence of ventilation on road tunnel fires with and without water-based suppression systems

Ying Zhen Li, Haukur Ingason
Abstract

Influence of ventilation on road tunnel fires with and without water-based suppression systems

Analyses of previous test data and theoretical analyses are carried out to investigate the influence of ventilation on fire development, toxic gas concentration, visibility and risk for fire spread to nearby vehicles, in a road tunnel without and with a water-based fire suppression system. In a tunnel without a fire suppression system, a slightly lower ventilation velocity is preferred to slow down the fire growth at the initial stage of evacuation. At the fire fighting stage the ventilation velocity can be adjusted up to critical velocity. In a road tunnel with a fire suppression system, a slightly higher velocity is recommended to reduce the toxic gas concentration and increase the visibility downstream.

Key words: road tunnel fire, ventilation, fire suppression, fire development, toxicity, visibility, fire spread

SP Sveriges Tekniska Forskningsinstitut

SP Technical Research Institute of Sweden

SP Report 2016:36


ISSN 0284-5172

Borås 2016
## Contents

- **Abstract** 3
- **Contents** 4
- **Preface** 6
- **Summary** 7
- 1 **Introduction** 8
- 2 **Influence of ventilation on fire growth rate (FGR)** 9
- 3 **Fire suppression – extinguishment mechanisms** 12
  - 3.1 Surface cooling 12
  - 3.2 Gas-phase cooling 12
  - 3.3 Dilution effects and heat capacity 13
  - 3.4 Radiation attenuation 13
  - 3.5 Kinetic and other factors 13
  - 3.6 Effect of ventilation 13
- 4 **Fire suppression - theoretical considerations** 15
  - 4.1 Effect of ventilation 15
  - 4.2 Criteria for system effectiveness 15
  - 4.3 Practical use 15
  - 4.4 Summary 16
- 5 **Tunnel fire tests with suppression systems** 17
  - 5.1 Design fire tests with suppression 17
  - 5.2 Toxicity tests with suppression 18
  - 5.3 Runehemar tunnel fire suppression tests 18
- 6 **Analysis of the effect of ventilation on fires without suppression** 20
  - 6.1 Fire development 20
  - 6.1.1 Long fuels 20
  - 6.1.2 Cubic shape fuels 21
  - 6.1.3 Short summary 23
  - 6.2 Toxic gases and visibility 24
  - 6.3 Fire spread to target 26
  - 6.4 Summary 28
- 7 **Analysis of the effect of ventilation on fires with suppression** 30
  - 7.1 Fire development with suppression 30
  - 7.1.1 Long fuels 30
  - 7.1.2 Short fuels 32
  - 7.1.3 Short summary 35
  - 7.2 Fire spread to target 35
  - 7.3 Toxic gases and visibility 36
  - 7.3.1 Wood pallet fires 36
  - 7.3.2 PE crib fires 38
  - 7.3.3 PUR crib fires 40
  - 7.3.4 Short summary 42
  - 7.4 Summary 43
- 8 **Conclusions** 45
9 References

10 Appendix I - Theoretical considerations – fire suppression

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>Initial burning region</td>
<td>47</td>
</tr>
<tr>
<td>10.1.1</td>
<td>Before activation</td>
<td>47</td>
</tr>
<tr>
<td>10.1.2</td>
<td>After activation of the suppression system</td>
<td>48</td>
</tr>
<tr>
<td>10.2</td>
<td>Spreading region</td>
<td>50</td>
</tr>
<tr>
<td>10.2.1</td>
<td>Before activation</td>
<td>51</td>
</tr>
<tr>
<td>10.2.2</td>
<td>After suppression</td>
<td>51</td>
</tr>
<tr>
<td>10.3</td>
<td>Fire spread to target</td>
<td>52</td>
</tr>
<tr>
<td>10.4</td>
<td>Comparison of water density required for the three regions</td>
<td>53</td>
</tr>
<tr>
<td>10.5</td>
<td>Global fire growth rate</td>
<td>54</td>
</tr>
<tr>
<td>10.6</td>
<td>Actual water flow rate</td>
<td>57</td>
</tr>
</tbody>
</table>
Preface

This work was funded by the Swedish Transport Administration (STA) which is greatly acknowledged. The work is a part of research programme aiming to improve road tunnel fire safety using more effective technical solutions with aid of scientific methods. A long term co-operation between SP Fire Research and STA has made this possible.

The authors would like to thank Ulf Lundström at STA for his support and encouragement to perform this study.
Summary

In fires without water-based fire suppression systems, the fire growth rate increases linearly with longitudinal ventilation velocity. Windbreaks reduces the fire growth rate by reducing the local velocities inside the fuel load. To reduce the heat release rate and also maintain certain smoke stratification at the early stage of evacuation, use of a low velocity is preferred. This is specifically important in a queue situation. A lower velocity results in a smaller fire size, improved stratification and lower risk for fire spread to nearby vehicles. Higher velocities increase fire size, destroy downstream stratification and increase risk for fire spread.

How the velocity should be adjusted depends on whether upstream backlayering is allowed and how long it is if so. This is related to the traffic situations and evacuation strategies for the tunnel. For example in the case of no queue formed downstream of the fire in a normal multiple lane unidirectional road tunnel, a velocity of approximately 3 m/s is preferred to control backlayering. However, in the case of a queue formed downstream of the fire, a velocity between 1.5 m/s and 2 m/s is recommended. This will reduce the risk for fire spread to nearby vehicles and improve initial evacuation conditions. Later at the fire fighting stage, a velocity slightly greater than the critical velocity (3 m/s - 3.3 m/s for most road tunnels) is preferred, to prevent any backlayering, and also to reduce the concentration of toxic gases and improve visibility far downstream.

Water-based fire suppression systems with side spray nozzles and a water density of 10 mm/min are able to effectively suppress the fire development after activation of suppression system. Although higher ventilation has a potential to compete with the suppression system, the test results show insignificant effect of ventilation on fire development after the activation. The fire development strongly depends on the activation time. Therefore it is recommended to early detect and identify the fire and to activate the suppression system. From the perspective of fire development, the ventilation has limited influence during the range of 1.5 m/s and 3 m/s after activation of the fire suppression systems with the designed capacity.

After activation of the suppression system, the influence of ventilation on toxic gas production is not very significant. For a location far downstream of the fire site, the average CO concentration with a lower velocity is expected to be higher and the visibility becomes lower. Therefore, from the perspective of toxic gas production and visibility, a higher velocity is preferred. From the perspective of fire spread to nearby vehicles, after activation of the suppression system, the risk for fire spread is significantly reduced and the influence of ventilation is expected to be insignificant. This is true especially when the period of transition from a high velocity to a low velocity is short. Overall, a slightly higher ventilation velocity, e.g. 3 m/s, is preferred in tunnels with fire suppression systems, with the main purpose to reduce the toxic gas concentration. However, a velocity of 6 m/s is not recommended as rapid flame spread is still possible within a certain time after activation of suppression.

If the fire suppression system has a lower capacity or the effectiveness of the system is lower, the effect of ventilation could be more important.
1 Introduction

In conjunction with the Transport Agency's revision of the Northern Link safety concept an international tunnel expert group has been engaged into the process. During the revision process, questions about the impact of ventilation on the fire spread and fire development before and after activation of the water-based fire suppression system were raised. When the word tunnel is used it refers to road tunnels and when ventilation is used it refers to longitudinal ventilation velocity.

The focus of engineering work and design of tunnel fire safety is on the fire development, especially the initial fire growth. The first ten or fifteen minutes of a fire are crucial for those who have to escape from the fire. A common component in most fires has been the significance of the vehicle type, position in relation to portals and other vehicles, the ignition source and the effects of the ventilation on fire growth rate (FGR). The focus of this report is on the last one, the effects of ventilation on the FGR both without and with water spray systems. The main question in the case of no water spray system is the choice of strategy in case of fire. In many road tunnels the piston effects create a certain longitudinal ventilation and maintain the velocities at relatively high levels, maybe 6 – 8 m/s. In queue situation the ventilation system maintain the velocity at levels higher than say 3 m/s.

One of the main issues for designers are what should the operator do in case of fire in these situations. Should they lower the ventilation velocity or maintain it at a similar level. In some projects it is recommended that it is lowered from the moderate velocity of 3 m/s to a lower velocity of around 1.5 m/s after a fire detection. If one chooses to maintain the ventilation velocity at around 3 m/s how much will we increase the risk for fire spread. If there is a water spray system, is this something that needs to be considered? Is it always acceptable to maintain the velocity at plus 3 m/s, both with and without water-based fire suppression systems. Other aspects to consider are the effects of increasing ventilation velocity on smoke production and smoke and toxic gases concentration on the downstream side, both with and without a water spray system.

The objective of this project is to investigate the effects of ventilation on the conditions in the tunnel both with and without a water spray system. Therefore it is necessary to determine the way the fire suppression system acts with varying ventilation conditions, and what parameters they are to determine the fire development in tunnels with suppression systems. The focus is the difference between the case of keeping/changing to 3 m/s and the case of changing to a lower velocity, e.g. 1.5 m/s, after detection of a fire in a tunnel with or without a fire suppression system.
2 Influence of ventilation on fire growth rate (FGR)

The ventilation rate plays an important role in the fire development. It mainly affects how initial flames are tilted and consequently how the flame spreads further within the fuel. High ventilation rates can potentially prevent continuous fire spread; example of such an ignition delay is on the running vehicles which come to a stop. The flames may suddenly burst out after the stop, and the fire starts to develop rapidly. Other example is the location of the initial fire on a given fire load in relation to the wind direction. There are examples of engine compartment fires that were prevented to spread to the cargo on a heavy goods vehicle (HGV) trailer as the longitudinal flow was in the same direction as the HGV vehicle. It is difficult to predict a potential fire growth from the incipient period to the continuous FGR period, where the heat release rate (HRR) continue to increase rapidly, and will lead to a fully developed fire if not intervened.

The HGVs consist of, or carry, highly flammable materials, and the fire spreads very rapidly with aid of the longitudinal ventilation inside the tunnel. The tunnel ceiling height also has a major effect on the outcome. In most of the Alp tunnel fires with numerous HGV vehicles involved occurred in tunnels with relatively low ceiling height, in the range of 4 – 5 m. Together with the longitudinal flow this combination becomes devastating for the FGR. The type of cover of the cargo is also a parameter that is of great importance and usually not mentioned in this context of FGR. Experiments have shown that the blockage to the cargo, especially in the front or rear of a trailer, can influence the FGR by a factor of two or more. This is extremely important to understand as the FGR is a key parameter for the fire safety design of tunnels. The effects become most important during initial evacuation of the tunnel users. Therefore, the effects of ventilation are most important during the evacuation period of tunnel users.

Although the ventilation velocity may result in an increase of the HRR and the FGR, the forced longitudinal ventilation is important and necessary to prevent the smoke back flow (backleyering) in most tunnel fires. It constitutes the basis for the design of critical velocity and therefore gets such high focus among tunnel engineers.

A common understanding among engineers and researchers is that the fire growth rate increases considerably with the ventilation velocity in a tunnel fire. The question is only what parameters dominate and really control how fast a fire grows from its initial conditions.

Not only are the local ventilation conditions important, but also other factors such as type and configuration of the fuel, and the position and extension of the flame. In a tunnel fire, the longitudinal ventilation plays a key role in the flame spread, thus it is much different from an open fire or a room fire. Moreover, the relationship between the FGR and the flame spread over the fuel surface in a ventilated tunnel fire is not clearly known. In order to obtain the effects on the FGR due to longitudinal ventilation, the fuel has to extend in the direction of the flame spread. If the fuel bed is short or cubical in shape, the effects of the ventilation are not expected to be as evident as if the fuel were geometrically elongated in the direction of the ventilation and thereby the flame spread. Example of such fuel loads are HGV trailers. Therefore, for fire loads such as HGV trailers or long vehicles, the effects of the ventilation become more definite. If the fuel load is cubical in shape or extends more in the perpendicular direction of the longitudinal ventilation, the opposite effects may be expected, i.e. increasing ventilation rate may slow down the FGR.
The theory of fire growth rates in tunnel fires [1] is suitable for fuels exposed to wind. In case that the fuels are not directly exposed to wind, the FGR could be expected to be lower, and thus the estimated FGR based on the proposed equations is also lower. Therefore the proposed method tends to be conservative. In the Tunnel Fire Dynamics book [2] there is an example showing how the ventilation effects of the FGR.

Example 1

Estimate the FGR for a 10 m trailer loaded with furniture and PUR mattress in a 6 m high tunnel. The total exposed fuel surface area of 150 m$^2$ consists of 80 % furniture and 20 % PUR mattress. The fuel load is assumed to be uniformly distributed in the trailer. The velocity in the vicinity of the truck in the tunnel is 2 m/s. How much will the FGR increase if the velocity is 3 m/s instead?

Solution: Find values of the material property $C_f$. The values are found in Table 5.1 in the Tunnel Fire Dynamic book [2], i.e. 3333 for furniture and 20000 for PUR mattress. The total wet perimeter of the fuel is $150/10=15$ m, including 12 m for furniture and 3 m for PUR mattress. Now we can use Eq. (5.26) to estimate the FGR:

$$\frac{dQ}{dt} = 1.2 \times 10^{-3} \times 2 \times (3333 \times 12 + 20000 \times 3) = 240 \text{ kW/s} = 14.4 \text{ MW/min}$$

If the longitudinal ventilation rate was 3 m/s instead the FGR would have been 21.6 MW/min. If the ventilation rate is lowered to 1.5 m/s, the expected FGR for the same fuel would be 10.8 MW/min. The FGR is reduced by 50 %, i.e. it is directly correlated with the reduction in the ventilation rate.

In a realistic vehicle fire, the fuels are complicated in structure and cannot be predetermined in most cases, e.g. fuel load and configurations for a HGV trailer. Most HGVs have rear doors and steel walls upfront, both of which block air movement into the fuel array. Further, the driver’s cab itself presents a degree of obstruction to the flow of air through the fuels. The rest of the cargo area that could be covered with thin polyethylene tarpaulins burns easily. Data from previous full scale tests can be used to simulate realistic HGVs fires. In the following some examples are given.

In the Runehamar tests, a polyethylene tarpaulin covered the entire volume with a fuel load (upfront ends, rear ends, sides and ceiling) and relatively soon after ignition the tarpaulin burned away on the upstream side of the fuel and the horizontal wind-aided flame spread inside the fuel stack was able to develop. This of course influenced the fire development drastically. If a windbreak in form of a board or steel sheet would have been mounted at the ends of the fuel load, especially the upstream end, a wake of circulating air would have been created inside the fuel load and the inside wind velocity would have been reduced considerably. This would have direct impact on the FGR.

In the testing of a water mist system in 2006 [3] it was reported that the ventilation velocity had a large effect on the FGR which consisted of piled wood pallets. Addition of upstream panels to block wind penetration into the fuel array, which consisted of piles of wood pallets, had a significant reduction in HRR of the fires. The tests revealed how large an effect of the design of the HGV itself may have on the fire development. Today, most of the large scale tests carried out with FFFS systems use windbreaks on both upstream and downstream side.

In large scale tests carried out in 2013 by SP with water spray systems, a comparison was carried out with and without windbreaks consisting of a thin steel sheets on the ends and
top of the fuel. The longitudinal velocity inside the tunnel was 3 m/s. The linear FGR for test 5 is about 5.5 MW/min and for test 6 it is 2.3 MW/min. This indicates a decrease of 58% in FGR after the placement of the windbreaks. In order to illustrate these effects an example is presented.

Example 2

Assuming a HGV load with 420 wood pallets is burning with and without a windbreak. What would the resulting wind velocity be inside the fuel load behind the windbreak? Assume that the longitudinal velocity in the tunnel without a windbreak is 3 m/s. The FGRs are 2.3 MW/min with a windbreak and 5.5 MW/min without a windbreak.

Solution: As the wet perimeter \( w_p \) in both cases is the same, the equivalent longitudinal velocity can be derived from the equation for fire growth rate. Since the relationship between the FGR and the longitudinal air velocity \( u_0 \) is linear, we obtain: \( u_{0\text{windbreak}} = \frac{2.3}{5.5} \times 3 = 1.25 \text{ m/s} \).

These results show the influence of ventilation and blockage of fuel on FGR. In the following focus is on the situation with water spray systems.
3 Fire suppression – extinguishment mechanisms

The mechanisms of extinguishment of fires using water-based fire suppression systems can be classified into two types: condensed phase suppression and gas phase suppression. In the condensed phase, surface cooling is the main mechanism. In the gas phase, the extinguishment mechanisms can be categorized into gas cooling, heat capacity and dilution effects, radiation attenuation and kinetic effects.

3.1 Surface cooling

The water droplets arriving at the fuel surfaces evaporate and take the heat away, which results in lower burning rates or extinction of the fire. This process is called surface cooling. Note that 1 kg of water can take away around 2.6 MJ heat by evaporation to water vapor at a temperature of 100 °C. For water-based fire suppression systems in tunnel fires, fuel surface cooling can be regarded as the primary mechanism of suppression of solid fuel fires. The cascading effect is deemed to be important for movement of water droplets through surfaces for typical three-dimensional complex fuels.

For surface cooling to be effective the water droplets must be able to penetrate the fire plumes. During this process, both the momentum and the evaporation of the water droplets dominate. Further, the flow rate of the water droplets surviving in this process and arriving at the fuel surfaces must be great enough to suppress the fire. For exposed solid fuels, traditional water spray systems could have better performance due to the large water flow rate and large water droplets. The amount of water required for fire suppression only needs to approximately equal the heat absorbed by the fuel surface, rather than the total HRR.

In a tunnel fire, surface cooling delays the fire growth rate by pre-wetting the nearby unburnt fuels. Further, the nozzles away from the fire source discharge water to the surface of the nearby vehicles, inhibiting vehicular fire spread. Surface cooling can easily delay or prevent ignition. Many tests have shown that even a small amount of water is capable of preventing fire spread to neighboring targets.

Water sprays discharged to the tunnel walls also provide protection for the tunnel structure. As a consequence, the requirement for passive protection could be lowered.

3.2 Gas-phase cooling

The water discharged from the nozzle is atomized into a large number of water droplets, and the total droplet surface areas are very large. Droplet evaporation results in efficient cooling of the flame and hot gases. The cooling of the flame raises the lower flammability limit of the oxygen and reduces combustion intensity. Further, heat feedback to the fire source is reduced. In a tunnel fire, the cooling of hot gases could increase the tenability conditions for evacuations, although the vapor introduced may somewhat lower down the tenability limit for the respiratory gas temperatures. For large tunnels fires the HRR is very high so extinction purely by gas phase cooling would require a very large amount of water, which is almost impossible. Therefore, this is not the main mechanism of fire suppression in tunnel fires.
The nozzles upstream of the fire source also contribute to fire suppression by cooling the gases flowing to the fire source if backlayering exists, and a small amount of the injected water droplets could also be blown to the nearby fire source.

### 3.3 Dilution effects and heat capacity

Dilution effects in water-based fire suppression systems are created by the evaporation of water drops. Note that due to the evaporation, the volume of water droplets expands by a factor of around 2700 at a temperature of 300 °C, which dilutes the concentration of both fuel and oxygen in the vicinity of the fuel surfaces and in the flame. At the same time, the much higher heat capacity of water vapor compared to air reduces the gas temperatures.

Dilution effects could be the key mechanism of suppression of gas and liquid fires, especially for water mist systems. However, in tunnel fires with forced ventilation, the water vapour could be blown away and the dilution effect could be significantly reduced.

### 3.4 Radiation attenuation

Similar to soot, water sprays and water vapors also absorb radiation. The radiation attenuation due to the water sprays depends on the water flow rate and the droplet sizes. For a continuous water curtain, the radiation attenuation could be very effective due to the high absorptance of the water. It is known that water vapor has a low absorptance, however, it could still play a key role due to the large volume.

Radiation attenuation reduces heat feedback to the fuel surface and lowers the HRR. It can also delay the fire growth rate and prevent fire spread to nearby vehicles in a tunnel fire.

On the other hand, water vapors produced by evaporation perform as a radiation medium, which absorbs heat from flames and hot gases, and also re-radiates the heat at a lower radiation intensity.

### 3.5 Kinetic and other factors

Kinetic effects include the impingement of water droplets on the fuel surface, turbulence induced by the water sprays, the interaction between the nozzles, and the effect of droplets on the flame temperature limit.

Other factors could include the effect of tunnel ventilation on the movement of water droplets and water vapors and the effect of tunnel walls.

These are only secondary effects and are not expected to significantly affect the performance of water spray fire suppression systems in tunnels, and therefore are not discussed further.

### 3.6 Effect of ventilation

From the above analysis, it is known that unlike a fire in a closed enclosure, the dilution effects and increase of heat capacity are generally not the key mechanisms of suppression
of a tunnel fire due to the use of forced ventilation that transports the water vapors and combustion products away from the fire.

To effectively suppress a tunnel fire, surface cooling is the main mechanism. Large droplets with large penetration capacity are therefore preferred in use. On the other hand, the effect of ventilation on movement of the large droplets discharged from normal nozzles is deemed to be insignificant.

Therefore the question about effect of ventilation on fire suppression is mainly a question about how the fire interacts with water sprays under varying ventilation conditions.
4 Fire suppression - theoretical considerations

A theoretical analysis of the ventilation effect on fire development in tunnels with water based fire suppression systems is carried out in Appendix I. The fuels are divided into three regions: initial burning region (region 1), flame spreading region (region 2) and target (region 3). The analyses show that the fire in the initial burning region is most difficult to suppress, followed by flame spreading region and then the fire spread to target.

4.1 Effect of ventilation

According to the analyses, the effect of ventilation on the effectiveness of a suppression system is clear. If the flame spread in the spreading region is suppressed or if the fire is extinguished, the ventilation has close to no influence on the performance of suppression system. However, if the flame spread is not suppressed, the fire continues to burn and the fire growth rate increases with the increasing ventilation velocity and the decreasing water flow rate.

4.2 Criteria for system effectiveness

To determine the effectiveness of a suppression system, criteria are needed to be defined. According to the analyses, it is clear that the main criteria that could be used is whether the flame spread in the spreading region is suppressed or not. In theory, if the flame spread is suppressed, the heat release rate after activation of suppression will decrease, and thus lower than that at the activation time. The fuel consumed during a fire is also limited to the initial burning region. In real cases both the heat release rate and the fuel consumed could be somewhat higher than the theoretical values, but the criteria could still be applied. Therefore to determine whether a fire is suppressed or not, the criteria could be defined as follows:

(1) The heat release rate after activation of the suppression system is not much greater than (or at the same level e.g. max 20% higher) that at the activation time;

(2) The fuel (or energy content) consumed after activation of the suppression system in a fire to that in a free burn fire is less than a given value, e.g. 20 %.

The use of these definitions are useful only if the systems are activated at the early stage of a fire (fire growth period). If the heat release rate has already reached the peak value, the use of the first criterion is invalid, and instead the second criterion is more realistic and logical.

4.3 Practical use

The analyses focused on suppression of fires directly exposed to water sprays. This however is probably not the case in reality. In practice, the vehicles could have thick ceiling covers and windbreaks (end blocks), the water sprays may not be able to reach the internal fuels, which makes suppression of this internal section impossible in theory as the key mechanism in the cases is surface cooling. The other mechanism could be very important, e.g. the cascading effect. This would mean that the water sprays cascades from the top and flows to other spaces by gravity and/or through surface movement. Further,
the impingement of the droplets on the fuels may splash to fuels further away. The change of fuel configuration due to either that the fuels are burnt out or the fuels fall down due to loss in structural integrity may affect the fire development and performance of the fire suppression system.

The analyses in the appendix considered two factors, i.e. $K_w$ and $K_p$. The physical factor $K_w$ accounts for how much the water spays can reach the fuel surfaces without a fire, and $K_p$ accounts for reduction in percentage of these water sprays that is lost on the way to the surface due to the fire plume in case of a fire.

Many of these parameters cannot be directly obtained from theoretical analysis but are case dependent. However, for a specific case, a useful correlation could be proposed taking all key parameters into account. Further, there is a need to carry out more researches on e.g. the penetration capability of water droplets under different conditions.

**4.4 Summary**

In theory, if the activation of a suppression system is prolonged (e.g. late activation), it is more difficult to suppress it. The reason is that the fire could grow more rapidly, and this also corresponds to a greater risk for fire spread to fuels nearby. Therefore, early activation is recommended from this point of view.

Suppression of fire spread to fuels nearby requires a much less water density. This explains why most suppression systems work well in prevention of this type of fire spread even operating with a low water density.

Penetration and transportation of water droplets to the fuel surfaces in the burning region and unburnt region could take long time in typical three-dimensional fuel configurations.

High ventilation has limited effect on burning in the initial burning region, but generally results in higher fire growth rate. Further, under high ventilation it is generally more difficult to detect the fire. Therefore in theory, a high ventilation case is worse than a low ventilation case in performance of fire suppression system.

For the case of most interest to this work, the key question is after detection of a fire, which ventilation velocity is preferred. The main difference that can be expected is the influence of ventilation on suppression of the burning in the spreading region (region 2). Although in theory, after activation of the suppression system the fire under higher ventilation could either grow more rapidly or decrease more slowly under 3m/s, this difference needs to be quantified.

As no such a test with varying velocities has been carried out, a good understanding of the mechanisms is required. In the following, test data are gathered and analysed together with some theoretical considerations.
5 Tunnel fire tests with suppression systems

Data from several test series are analyzed, including the model scale tests with design fires [4], the model scale tests with toxicity [5], and the Runehamar tunnel fire suppression tests [6, 7].

Note that in all the model scale tests (a scaling ratio of 1:4), the velocity should be scaled up to full scale by a factor of 2. The factor is also 2 for time, but it is 32 for heat release rate. Therefore the full scale velocities of 1.5 m/s and 3 m/s correspond to 0.75 m/s and 1.5 m/s in the model scale.

In the following analysis, by default, the water density is 10 mm/min in full scale and 5 mm/min in model scale (corresponding to 10 mm/min in full scale).

5.1 Design fire tests with suppression

The Froude scaling technique has been applied in the tests. Experience of model tunnel fire tests shows a good agreement between model scale and large scale test results on many focused issues, e.g. fire development [8]. Wood pallets were used as fire sources based on a new scaling method. The validation tests reported confirmed the accuracy of the scaling of wood pallet fires [9].

A total of 18 tests were carried out in the 1:4 model scale tunnels with water-based fire suppression systems together with one free-burn test [4]. The key parameters including fuel load covers, activation time, water flow rate, nozzle type, ventilation velocity, sprinkler section length and tunnel width were tested. The test set-up and measurements are shown in Figure 1. The model tunnel itself was 15 m long, 2.8 m wide and 1.4 m high. The scaling ratio was 1:4. This suggests that the corresponding full scale dimensions would be 60 m long, 11.2 m wide and 5.6 m high, respectively. In some tests, the model tunnel width was changed to 1.88 m, corresponding to 7.5 m in full scale.

Three types of nozzles were tested, including one scaled T-Rex nozzle and two normal nozzles K5 (K-factor 5) and K9 (K-factor 9). The full scale T-Rex nozzles are now manufactured under the name of TN-25. The sprinkler section length was either 12.5 m (50 m in full scale) or 7.5 m (30 m in full scale). A measured ceiling gas temperature of 141 °C is used as the criteria for fire detection in the tests, that is, a tunnel fire is detected after a gas temperature of 141 °C is measured by one of the ceiling thermocouples (T5 to T9). The corresponding fire is expected to be large enough to be detected easily by most of the detectors, that is, the criterion tends to be conservative. Further, note that in reality after fire detection, it takes some time for the tunnel operators to respond to the situation. This delay is also simulated and by default set to be 1 min in full scale, i.e. 0.5 min in 1:4 model scale. In the tests, different delay time was tested.

The fuel load was designed to produce a maximum HRR of approximately 100 MW in full scale, excluding the target.
5.2 Toxicity tests with suppression

The test set-up of this series of tests is similar to that of the design fire test series [5], as shown in Figure 2. The main difference is that the water spray system tested only consisted of T-Rex nozzles, and covered a region of 7.5 m, corresponding to 30 m in full scale. Another difference is that in all the tests no ceiling cover and windbreaks were used. The purpose of the tests was to investigate the toxic gas production after activation of a suppression system.

The designed water flow rate is 5 mm/min (full scale 10 mm/min). The longitudinal ventilation velocity in the tunnel was set to be 0.75 m/s, 1.5 m/s, or 3 m/s (or 1.5, 3 and 6 m/s in full scale, respectively).

Vehicle mock-up was simulated using three different types of fuels, i.e. two piles of wood pallets each with 10 layers, polyethylene (PE) cribs and polyurethane (PUR) cribs. The fuels were placed in a 1 m diameter steel pan with approximately 80 mm high rims. In some tests the front, the back side and top of the fire load were covered by steel plates.

5.3 Runehamar tunnel fire suppression tests

A total of 6 fire suppression tests were carried out in the Runehamar tunnel situated about 5 km from Åndalsnes in Norway in 2013 [6, 7]. It is a two-way asphalted road tunnel that was taken out of use in the late 1980s. It is approximately 1600 m long, 6 m high and 9 m wide with a cross-section of about 47 m². The tunnel has an average uphill slope of 0.5% up to about 500 m from the east portal (where the fans are located) 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. The fire was located 600 m from the east portal, i.e. on the plateau section of the tunnel. The tunnel is protected with shotcrete at the test location.

The pipe was shortened to 30 m, and the total water flow is 2250 l/min as the water requirement in order to deliver 10 mm/min at the 30 m section was 2250 l/min. A 600 m long ground pipe with a diameter of 140 mm (inside diameter of 127 mm) delivered the water from the water tank to the 30 m long deluge system in the ceiling. The ground pipe was connected with the ceiling pipe as shown in Figure 3. The water tank had a capacity of 230 m³, which was enough to maintain at least 90 min delivery of water.

The gas temperatures, gas concentrations, visibility, water flow rate and water pressure, were all registered every second. The test set-up is shown in Figure 3.

Figure 3  The layout and identification of instruments in the series of tests (dimensions in m).
6 Analysis of the effect of ventilation on fires without suppression

Various vehicles in tunnels could be classified into two fuel types: short fuels of cubic shape or long fuels such as HGV trailer. It is found that the effect of ventilation on these two types of fuels is different to some extent. But a fire starts at the downstream end of a long vehicle is expected to be similar to a fire with a short fuel load. However, the worst cases with long fuels and rapid fire growth potentials are of most interest from the perspective of fire development. By default a fire with a long fuel indicates that the main flame spread mechanism is the longitudinal flame spread [1].

Note that in the design fire tests [4] and in the Runehamar tunnel fire tests [6, 7], heavy goods vehicle mock-ups were used while in the toxicity tests [5] short fuels of cubic shape were tested.

6.1 Fire development

6.1.1 Long fuels

A general discussion on influence of ventilation on fire development has been presented in Section 2. By long fuels it is meant that the fuel is much longer than its height or width. The basic findings are that for HGVs fires the ventilation has very limited effect on maximum heat release rate, but the fire growth rate (FGR) increases linearly with ventilation velocity for fuels exposed to wind (without windbreak). In Figure 4 the fire growth rate as a function of velocity in tunnels with no suppression and no windbreak is plotted. Clearly, the fire grows more rapidly at a higher ventilation velocity. In Figure 4, \( \dot{Q}^* \) is dimensionless heat release rate, \( t \) is time, \( u_o^* \) is dimensionless longitudinal ventilation velocity, \( H \) is tunnel height, \( C_f \) is a material property, \( H \) is tunnel height and \( w_p \) is wet perimeter of the fuel across one cross section.

\[
\frac{\dot{Q}^*}{t} = C_f \frac{w_p}{H^{3/2}}
\]

Figure 4 The fire growth rate as a function of ventilation velocity in tunnel fires [1].
Note that if there are windbreaks especially the front windbreak, the ventilation conditions in the main fire load will be very different as the local velocities are much lower behind the windbreak. In such cases, the effect of tunnel ventilation on fire development could be reduced significantly. In Example 2 given in Section 2, the estimated effective velocity for the fire development with windbreaks is 1.25 m/s, compared to the longitudinal tunnel velocity of 3 m/s. The corresponding FGR is 2.3 MW/min with a windbreak, in comparison to 5.5 MW/min without a windbreak. This clearly shows the effects of blocking the fuels directly exposed to the tunnel ventilation.

### 6.1.2 Cubic shape fuels

In the toxicity tests with fire suppression, some free-burn tests with varying ventilation velocities were also carried out for comparison. Note that these fuels are of cubic shape, different to the ones used in full scale tests and other model scale tests. By cubic shape fuels it is meant that the length, height and width is about the same. These tests will be discussed in the following.

#### 6.1.2.1 Wood pallet fires

Figure 5 shows the effect of ventilation velocity on heat release rate in the free-burn tunnel fire tests (model scale 1:4). The maximum heat release rate for both 1.5 m/s and 3 m/s is approximately 1.9 MW. In test 1 with 1.5 m/s, the value is around 1.7 MW before the collapse of the wood pallet that results in the rise of the heat release rate to 1.9 MW. Clearly it shows that the fire in test 14 with 3 m/s grows up more rapidly, that is, the fire growth rate is greater due to higher ventilation velocity.

![Figure 5](image)

*Figure 5  Heat release rate in the free-burn tests at different velocities (Wood pallet fires).*

#### 6.1.2.2 PE crib fires

Figure 6 shows the effect of ventilation velocity on heat release rate in the free-burn tunnel fire tests with PE crib fires. The maximum heat release rate in the test with 1.5 m/s is slightly lower than that with 3 m/s and the highest value is registered in the test with 0.75 m/s. Although the influence of ventilation velocity is different to what has been
found for fires with long wood pallet piles, it is still clearly shown that the effect of ventilation velocity on the maximum heat release rate is insignificant. It can also be found that the fire growth rate does not show a monotonous increase with the ventilation velocity. The reason could be that the crib is of a cube shape and longitudinal flame spread (leaning inside the fuel) does not dominate. For such types of fuel of short length in longitudinal direction, transverse flame spread (lateral flame spread) could be as important as longitudinal flame spread.

Figure 6  Heat release rate in the free-burn tests at different velocities (PE crib fires).

The fire with coverage in test 21 develops much more slowly as the wind is not directly blown into the fuel. However, the maximum heat release rate is approximately at the same level as the fires without coverage.

6.1.2.3  PUR crib fires

Figure 7 shows the effect of ventilation velocity on heat release rate in the free-burn tunnel fire tests. Clearly it shows that the effect of ventilation velocity on the maximum heat release rate is insignificant (the difference between 1.5 m/s and 3 m/s is less than 10 %). It also shows that the fire growth rate is slightly greater for 3 m/s.
6.1.3 Short summary

If a fire starts at the upstream edge of a long fuel, regardless of windbreaks, the key flame spread mechanism at the main fire development stage is the longitudinal flame spread (dominated by the flame spread along the fuel). Therefore the fire growth rate increases linearly with ventilation velocity, as discussed in Section 2. This should be considered as the key mechanism for HGV fires. The case with long vehicles could be regarded as the worst scenario as the fire could grow very rapidly.

In such a case, the fire growth period could be divided into two stages: the initial stage (incipient stage) and the linear growth stage. The heat release rate could therefore be expressed as sum of that in the initial stage and that in the linear growth stage:

\[ \dot{Q}(t) = \dot{Q}(t_o) + au_o(t - t_o) \]  

where \( \dot{Q} \) is heat release rate (kW), \( t \) is time (s), \( t_o \) is time at the end of initial stage (s), \( u_o \) is longitudinal velocity in the tunnel (fresh air, m/s), and \( a \) is a coefficient based on the fuel material properties and the wet perimeter of the fuel, see [2]. Here it is assumed that the fire detection time is close to \( t_o \), after which the ventilation is adjusted to the designed value.

This indicates that change to a lower velocity slows down the fire growth and therefore corresponds to a better scenario from the perspective of design fires.

In contrast, for short fuels without windbreaks (or fires of cubic shape), the heat release rate may not increase linearly with the ventilation velocity. The flame from the ignition source could be blown to the end of the fuel and thus no longitudinal flame spread is formed. The fires may develop more rapidly under a lower ventilation rate, as illustrated in Section 6.1.2. This could be the case with a car fire. For example, a car fire develops more rapidly if the fire initiated at a back tyre compared to at a front tyre. Similar phenomenon was observed in the Second Benelux tunnel fire tests [10]. However, as mentioned, the worst case with a HGV fire is still focused on in this work.

Therefore, for a HGV fire, the change to a lower velocity after detection of a fire corresponds to a better scenario from the perspective of design fires. The question is...
which value is best suitable for the velocity. Under 1.5 m/s, the backlayering will occur with a length of approximately 30 m for a 3 MW fire, 50 m for a 6 MW fire, and 70 m for a 10 MW fire [11]. If backlayering of such a length is acceptable, it is appropriate to use 1.5 m/s. Or else increase it to approximately 3 m/s. Decreasing the velocity further to e.g. 1 m/s may not significantly affect the fire development for fires with heat release rates lower than e.g. 30 MW. But it could have strong influence on fire development for larger fires with a certain reduction in heat release rate but potentially more toxic gas releases [12].

6.2 Toxic gases and visibility

Here we consider a typical HGV fire with the longitudinal fire spread as the main spread mechanism. The initial stage could correspond to a heat release rate of several MW. It could be assumed that at the moment of fire detection, the fire is approximately of this size and the time corresponds to \( t_0 \). After this time, the fire is assumed to be in the linear growth period.

It could also be assumed here that the yields of CO and soot, i.e. \( \text{Yield}_{\text{CO}} \) (kg/kg) and \( \text{Yield}_{s} \) (kg/kg), are not sensitive to ventilation conditions for well ventilated fires. In the fire growth period, the average CO concentration (mass, kg/kg) at a certain distance downstream of the fire can therefore be expressed as:

\[
Y_{\text{CO}} = \frac{[\dot{Q}(t_0) + au(t - t_0)]\text{Yield}_{\text{CO}}}{\Delta H_c \rho_o u A_T} = \frac{\dot{Q}(t_0)\text{Yield}_{\text{CO}}}{\Delta H_c \rho_o u A_T} + \frac{a(t - t_0)\text{Yield}_{\text{CO}}}{\Delta H_c \rho_o A_T}
\]

(2)

where \( \Delta H_c \) is heat of combustion (kJ/kg), \( \rho_o \) is fresh air density (kg/m\(^3\)), \( A_T \) is tunnel cross-sectional area (m\(^2\)).

Note that \( t_0 \) and \( \dot{Q}(t_0) \) are the initial conditions and thus assumed to be fixed. The average CO concentration is therefore not sensitive to the velocity as the second term on the right hand side is independent of the velocity. In reality, the average CO concentration slightly decreases with the increasing velocity (see the first term). Or mostly the average CO concentrations in these two cases are approximately the same.

Note that the fire develops faster at a higher velocity. After the heat release rate at a high velocity reaches its peak value, the average CO concentration is approximately constant while the value for a low velocity continues to increase as the fire continues to grow. During this period, the average concentration at a lower velocity is higher.

When the fire reaches the maximum heat release rate, the average CO concentration at a certain distance downstream of the fire can be expressed as:

\[
Y_{\text{CO}} = \frac{\dot{Q}_{\text{max}} \text{Yield}_{\text{CO}}}{\Delta H_c \rho_o u A_T}
\]

(3)

It is known that the maximum heat release rates for HGV fires are insensitive to the ventilation. This indicates that the average CO concentration decreases with the increasing velocity at this moment, assuming the CO yield is insensitive to velocity. This assumption will be discussed further in Section 7.3. It is shown that in some cases the CO yield under a low velocity might be slightly higher.
An illustrative figure is shown in Figure 8. The y axis is only an average CO concentration index used for comparisons under different conditions. It is assumed that at 5 min when the heat release rate of a HGV fire is 5 MW at an initial velocity of 6 m/s, the fire is detected. Then the ventilation velocity is either keeping at 6 m/s, change it to 3 m/s or to 1.5 m/s. The maximum heat release rate is assumed to be 100 MW. It is also assumed that the fire growth rate with 6 m/s is 10 MW/min, and therefore it is 5 MW/min with 3 m/s and 2.5 MW/min with 1.5 m/s. Clearly, at the early stage the average CO concentrations under different ventilation conditions are approximately the same, and slightly higher for low velocities. In contrast, at a higher velocity the average CO concentration reaches the peak value earlier, and the peak value is lower than that with a lower velocity. It should, however, be kept in mind that the main concern in this context is the early stage, e.g. early several minutes of evacuation. Therefore the difference in average CO concentration for different ventilation velocities are approximately the same during this period. In other words, at the early stage of a fire, the influence of ventilation on average CO concentration downstream is insignificant.

![Figure 8](image_url)

**Figure 8**  Comparison of CO concentration indexes with three velocities.

In the above analysis, we focus on the average downstream concentration. In the vicinity of the fire, e.g. between the fire and 50 m downstream, the scenario could be slightly different as certain smoke stratification could exist in the case with 1.5 m/s and thus the environment could be better for evacuees. However, for locations further downstream, the stratification could not exist and use of the average concentration is reasonable.

The visibility in the growth periods could be expressed as follows:

\[
V_v \propto \frac{u_a A_f}{\dot{m}_f \text{Yield} \sigma_s} = \frac{A_f \Delta H_c}{\text{Yield} \sigma_s [\dot{Q}(t_a)/u_a + a(t-t_a)]}
\]

(4)

where \( \dot{m}_f \) is fuel mass loss rate (kg/s), \( \sigma_s \) is a specific mass extinction coefficient (it can be regarded as constant, m\(^2\)/kg).

At the maximum heat release rates (\( \dot{Q} = \dot{Q}_{\text{max}} \)), the visibility, \( V_v \) (m), could be expressed as:
Clearly, similar conclusions can be drawn for the visibility.

It should be kept in mind that the focus is the early stage of a fire, corresponding to the fire growth period. Therefore Eq. (2) and Eq. (4) are more useful in our comparisons. In this period, the effect of ventilation on toxic gas concentration and visibility is considered to be insignificant, assuming that the yields of CO and soot are constant.

The toxic gases and visibility for short fuels will be discussed further in Section 7.3. There will it be found that different to wood and PUR fires, the CO yield for the PE fires at 0.75 m/s (full scale 1.5 m/s) tends to be higher than 1.5 m/s and 3 m/s. This may partly be due to the uncertainty of estimation. In reality, estimations of fuels in the tunnels indicates that plastic fuels occupies approximately 18 % of the total fuels and the proportion of PE is even less. Therefore the possible increase in the total CO production rate in case of a tunnel fire is considered to be limited. Despite this, a velocity lower than 1.5 m/s is not recommended for fires involving PE.

6.3 Fire spread to target

From the model scale tunnel fire tests focusing on ceiling jet characteristics [13], it is known that the incident heat flux needs to exceed approximately 20 kW/m², in order to ignite the targets both on the floor and at 2 m above the floor. This criterion is not sensitive to ventilation conditions. Therefore, the effect of ventilation on fire spread is dependent on how ventilation affects the heat release rate and thereby the heat fluxes.

The range of fire spread to targets downstream of the fire under different ventilation conditions has also been investigated [13]. The basic finding is that high ventilation slightly reduces the risk for fire spread to vehicles far downstream by ceiling smoke radiation. The main reason is that under high ventilation the gas temperature is slightly lower but it results in a much lower radiation heat flux given that the heat flux varies as 4th power of the absolute gas temperature. Therefore a high ventilation of 3 m/s in fact corresponds to a slightly lower heat flux and also a slightly lower risk for fire spread by the ceiling smoke radiation, compared to 1.5 m/s. Note that this fire spread mechanism by ceiling smoke radiation is mostly responsible for fire spread to vehicles downstream in a large fire.

One special case is that a flame inclined by wind could emit high enough radiation to ignite the nearby vehicles. This fire spread by wind inclination and flame radiation mostly occurs at the early stage of a fire, which is of most interest to this study. Previous fire spread tests carried out in the Törnskog tunnel with 5.5 MW fire and velocity of 5.5 m/s and 3 m/s show that the difference is limited. One reason is that the flame angle is insensitive to the ventilation for velocity larger than 3 m/s. Therefore the flame shapes are very similar under these two velocities. The difference between 1.5 m/s and 3 m/s, however, is larger. Note that this fire spread mechanism by wind inclination and flame radiation is mostly responsible for fire spread to nearby vehicles at the early stage of a fire.

In the following, examples of fire spread by wind inclination and flame radiation are given in Figure 9. It is assumed that the fire has a radius of 0.75 m and the critical heat flux for fire spread is approximately 20 kW/m². Note that tests in the Törnskog tunnel showed slightly higher critical heat fluxes. This could mainly be due to the convective
cooling of the fuel surface and dispersion of the ignitable vapors at the fuel surface, and also increased heat loss to the backside of the fuel. In Figure 9 the critical distance for fire spread increases with the fire size or heat release rate. The values in Figure 9 should be interpreted in such a way that within this distance, or shorter than this distance, the object will ignite. It also increases with the increasing longitudinal velocity, meaning that it becomes easier for spread to neighboring vehicle at a higher velocity. However, it can be seen that the risk for fire spread by inclination and flame radiation is more related to the fire size rather than longitudinal ventilation rate.

**Figure 9  Critical distance to the fire center as a function of ventilation velocity.**

Clearly, the critical distance for fire spread by wind inclination and flame radiation is sensitive to velocity when the velocity is low, i.e. lower than 2 or 3 m/s. The difference between 3 m/s and 6 m/s is much smaller. The difference between 3 m/s and 1.5 m/s is 0.2 m for 3 MW, 0.5 m for 6 MW and 0.9 m for 10 MW. Therefore the difference is in fact not so large.

Note that in the estimations of these critical distances for fire spread by wind inclination and flame radiation, the fuels are assumed to be exposed to the wind. However, this may not be true in most practical cases. For example, for a fire in a HGV engine compartment, the existence of driver cabin blocks the wind and the actual velocity here is much lower than the actual ventilation velocity, and therefore the flame may not be affected by wind so significantly. In other words, a smaller critical distance can be chosen. Moreover, the critical distance is measured from the centre of the fire source. Therefore this distance is not the interval distance between the fire vehicle and nearby vehicle. Therefore the location of the starting fire in a vehicle plays an important role in the possible fire spread. It should be kept in mind that over 10 MW, the flame height is mostly greater than tunnel height and thus the flames impinge on the ceiling and extends along the tunnel. The heat flux cannot be estimated using the point source method. Therefore extrapolation beyond 10 MW is not accurate.

For large fires, the fire spread to far downstream is possible by ceiling smoke radiation. By recalling the previous discussion, a high ventilation velocity of 3 m/s corresponds to a slightly lower risk for the fire spread by ceiling smoke radiation, compared to 1.5 m/s.
In summary, a velocity of 3 m/s corresponds to a slightly higher risk for fire spread by wind inclination and flame radiation to nearby vehicles, while it indicates a slightly lower risk for fire spread by ceiling smoke radiation to vehicles further downstream. In general, the risk for fire spread to neighboring vehicles in a queue situation with ordinary passenger cars is not that obvious as practicing engineers tend to believe. There is very little experimental data available to verify this, but the calculations showed here indicate this as a fact at least for tunnels with ceiling heights over 5 m. Further research is needed in real tunnels with real vehicles and ventilation conditions.

6.4 Summary

In a fire without fire suppression, the fire growth rate increase linearly with ventilation velocity. To reduce the heat release rate and also maintain certain smoke stratification at the early stage, it is better to use a low velocity, preferably between 1.5 m/s and 2.0 m/s.

In the vicinity of the fire, e.g. between the fire and 50 m downstream, a lower velocity than 1.5 m/s would result in acceptable smoke stratification but further downstream, 1.5 m/s would result in slightly higher average CO concentration and lower visibility. The difference is negligible unless the heat release rate exceeds 50% of the peak value.

Compared to 1.5 m/s, a velocity of 3 m/s corresponds to a slightly higher risk for fire spread (by wind inclination and flame radiation) to nearby vehicles in a queue situation, while it indicates a slightly lower risk for fire spread (by ceiling radiation) to vehicles far downstream.

From the perspective of toxic gas concentration and visibility, increasing the velocity slightly reduces the CO concentration and increases visibility far downstream at the early stage, especially for the PE fires. When the heat release rate approaches the peak value, the situations far downstream are much better at a higher velocity.

Therefore, it is difficult to find out an optimal ventilation velocity as the ventilation has different effects at different locations and at different stages of the fire. But still there are some recommendations that can be given here.

At the beginning of a fire, evacuation is the key issue. A lower velocity yields a smaller fire size, good stratification, and lower risk for fire spread. Therefore it is recommended to use a low velocity at this stage. However, it is not recommended to lower it down to a value below 1.5 m/s. At a velocity of 1.5 m/s, the backlayering will occur with a length of approximately 30 m for a 3 MW fire, 50 m for a 6 MW fire, and 70 m for a 10 MW fire.

How the velocity should be adjusted depends on whether upstream backlayering is allowed and how long it is if so. This choice is related to the traffic situation and the evacuation strategy of the tunnels.

In most cases, before a fire starts in a vehicle in an multi-lane unidirectional tunnel, there would be no queue formed in the tunnel both upstream and downstream of the fire. After a fire starts, the vehicles downstream are mostly able to drive out of the tunnel, while the vehicles upstream of the fire (behind the incident one(s)) most likely stop and maintain stationary. Therefore, a risk of a queue upstream of an incident site is probably high. In such cases, an existence of long backlayering should not be allowed, and thus a velocity used should be approximately equivalent to, i.e. around 3 m/s - 3.3 m/s for most of road tunnels. This would increase the risk of fire spread and increase the fire size, but in normal sized multi-lane unidirectional tunnel this should not create any non-manageable problems on the downstream side.
However, before a fire starts in a vehicle, if long queues are formed both upstream and downstream of the fire site (too many stationary/very slow-moving vehicles), a moderate velocity between 1.5 m/s to 2 m/s is recommended. Or if there are not so many vehicles running in the tunnel and the vehicles upstream can turn around and drive out of the upstream tunnel portal, the same recommendation applies here.

At the fire fighting stage, a larger velocity is preferred, to prevent the backlayering, and also to reduce the concentration of toxic gases and visibility far downstream. The velocity should be slightly higher than the critical velocity, i.e. around 3 m/s - 3.3 m/s for most of road tunnels. A velocity even slightly lower than the critical velocity is not recommended as for a large fire, the firefighter may not be able to stand 10 m upstream of the fire when the backlayering is 10 m. Therefore the value cannot be less than the critical velocity in such cases. On the other hand, the velocity is not recommended to be significantly higher than critical velocity. The reason is that in some cases early intervention may be achieved where the fire still has high potential to develop further and high ventilation could cause rapid growth.

It should be kept in mind that if the same fans are operating during the whole fire period, the tunnel velocity generally decreases with the increasing heat release rate and the time, due to the increasing flow resistance mainly caused by hot gases. Further, special attention should be paid to tunnels with large slopes as the buoyancy force may be significantly larger than what is expected when a fire occurs in its vicinity.
7 Analysis of the effect of ventilation on fires with suppression

7.1 Fire development with suppression

7.1.1 Long fuels

7.1.1.1 Design fire tests

Wood pallets were used as fuels with a maximum heat release rate in the free burn test of approximately 3 MW (96 MW in full scale) excluding the target.

Figure 10 shows the effect of ventilation velocities on the performance of the fire suppression with the K5 nozzles and an activation delay of 1 min. The tests correspond to Test 3 and test 6, both with windbreaks but without ceiling coverage. Clearly, the fire was suppressed in both tests. Under low ventilation, heat based fire detection systems can be triggered earlier and fire suppression was activated earlier. Thus the heat release rate was smaller at the activation time. Also note that the fire grows up more slowly in test 6 with a ventilation velocity of 0.5 m/s (1 m/s in full scale).

![Figure 10](image)

Figure 10  Effect of ventilation velocity on heat release rate in the K5 tests without ceiling coverage.

Tests with and without windbreaks (end blocks) were carried out with K5 nozzles. As the main difference between these two cases is the effect of local ventilation on fire development, some indications could be obtained from the comparison.

Figure 11 shows the effect of end blocks on the performance of the fire suppression system with an activation time delay of 0.5 min. Note that both tests were carried out without ceiling coverage. In the test without end blocks, the fire was difficult to ignite, and thus the upstream end block was still used for the early 2 minutes solely for the ignition purpose and removed afterwards.
Clearly, there exists a huge difference between the tests. The fire in test 1 with end blocks was suppressed immediately after activation of the suppression system, however, the fire in test 9 without end blocks had a maximum heat release rate of 1.35 MW (43 MW).

There could be two reasons for the difference. Firstly, the activation heat release rate in the test without wind breaks is around 600 kW, compared to around 200 kW in the test with windbreaks. Secondly, the higher ventilation could stimulate fire growth within a certain time after activation of the suppression system. Both the larger activation heat release rates and the higher ventilation velocity results in more rapid flame spread in the main fire load if the flame spread after activation of the suppression system indeed occurs, and also causes more difficulty in suppression for fuels directly exposed to wind.

If there are windbreaks in both tests and after activation of the suppression system the velocity changes from a higher value (e.g. 3 m/s) to 1.5 m/s, the influence of ventilation is expected to be very different, as there could only be a small change in the local ventilation velocities in the main fuel load. So the comparisons presented here are used for information only.

![Figure 11](image_url)  
**Figure 11**  Effect of end blocks on heat release rate in the tests without ceiling coverage with normal K5 nozzles.

### 7.1.1.2 Runehamar tunnel fire suppression tests

All the tests were carried out under around 3 m/s. But the tests with and without windbreak could be useful for understanding of the ventilation effect.

The heat release rates of these two tests are compared in Figure 12. These two tests with T-Rex nozzles were similar to the comparisons that we made earlier to the two tests in the design fire test series with K5 nozzles. But note that in the full scale tests ceiling covers were always used.

The activation heat release rate is around 14 MW for test 2 with windbreaks while it is 25 MW for test 5 without windbreaks.
It can be seen that the fire without windbreak develops much more rapidly due to the strong local ventilation. This correlates well with the results with K5 nozzles in the design fire test series without ceiling cover. The activation HRR in the K5 nozzle test without windbreak is around 18 MW in full scale. In both model scale and full scale tests without windbreak the maximum heat release rate is around 40% of the maximum HRR in a free-burn test.

It is also shown in Figure 12 that the fires with and without windbreaks lasts for closely the same period, i.e. approximately 45 min before they decreased to 5 MW.

![Figure 12](image.png)

**Figure 12**  
Comparison of heat release rates in the full scale suppression tests with and without windbreaks (Wood pallet fires).

The same reasons as explained previously are responsible for the faster fire growth in this test.

### 7.1.2 Short fuels

Results from the toxicity tests will be analyzed in the following with a focus on the effect of ventilation.

#### 7.1.2.1 Wood pallet fires

In the free burn fire tests with wood pallets, the maximum heat release rate is approximately 1.8 MW (58 MW in full scale).

Figure 13 shows comparisons of heat release rates in fire suppression tests for a velocity of 1.5 m/s (3 m/s) and 3 m/s (6 m/s) with wood pallet fires. The heat release rate at the activation time was 750 kW (24 MW) for 1.5 m/s and 550 kW (18 MW) for 3 m/s. For both velocities, the heat release rate decreased immediately after the fire suppression system was activated. In other words, the wood crib fire was effectively suppressed at both velocities.

Clearly, the fire grows more rapidly with 3 m/s. It can be known that the total energy consumed in the test with 1.5 m/s and earlier activation is only slighter higher than that with 3 m/s, and the difference between them is rather limited.
7.1.2.2 PE crib fires

In the free burn fire tests with PE cribs, the maximum heat release rate is approximately 3 MW (96 MW in full scale). Figure 14 shows comparisons of heat release rates in the fire suppression tests for a velocity of 0.75 m/s, 1.5 m/s and 3 m/s, respectively. In full scale these velocities corresponds to 1.5, 3 and 6 m/s, respectively.

In all the tests the fires without coverage are suppressed immediately after activation of the fire suppression system, even if the fire size at activation is close to the maximum size in a free-burn test. Note that the heat release rate curve for 0.75 m/s deviates from the others. This should be due to the influence of ignition source and the short fuel bed, given that the fuel and the ignition source are directly exposed to wind.

Figure 14 Comparison of heat release rates in the free burn test and fire suppression tests under 0.75 m/s, 1.5 m/s and 3 m/s (PE crib fires).
Test data show that the influence of ventilation between 0.75 m/s and 3 m/s on the fire development after activation of the suppression system is insignificant. It should be kept in mind that all the fires were immediately suppressed.

### 7.1.2.3 PUR crib fires

In the free burn fire tests with PUR cribs, the maximum heat release rate is approximately 1.8 MW (58 MW in full scale). The velocity of 0.75 m/s was not tested for PUR crib fires. Therefore only results with 1.5 m/s and 3 m/s are presented.

Figure 15 shows the comparison of heat release rate curves in PUR crib tests with suppression under 1.5 m/s and 3 m/s. The red lines correspond to 1.5 m/s while the blue lines 3 m/s.

Clearly, under both 1.5 m/s and 3 m/s, the heat release rates decrease immediately after activation of the suppression system, indicating that the fires are effectively suppressed.

It is also shown that the energy content consumed during the tests with 3 m/s (indicated by the area below the solid line) is slightly higher than that with 1.5 m/s. It should however be noted that the heat release rate at activation is also slightly higher under 3 m/s. Therefore, this increase in energy content consumed could be due to both the later activation and higher ventilation velocity. Despite this, it can be concluded that the influence of ventilation between 1.5 m/s and 3 m/s on the fire development is limited after activation of the fire suppression system for the PUR crib fire.

It should be kept in mind that all the fires were immediately suppressed. It could however be expected that if the fire is not effectively suppressed and continues to spread, the influence of ventilation could be more significant.

![Figure 15](image-url)  
**Figure 15** Comparison of heat release rates in the free burn test and fire suppression tests for velocities of 1.5 m/s and 3 m/s (PUR crib fires).
7.1.3 Short summary

Fire suppression systems with side spray nozzles and a water density of 10 mm/min are able to effectively suppress the fire development after activation of the suppression system. Although higher ventilation has more potential to compete with the suppression system, the test results show insignificant effect of ventilation on fire development after the activation. This could be largely due to the effectiveness of the system. If the water density is much lower or the effectiveness of the system is lower (e.g. nozzles like K5), the ventilation effect may be more significant.

The fire development strongly depends on the activation time. The recommendation is therefore to detect and identify the fire, and activate the suppression system as early as possible.

In the case of most interest, the initial velocity of around 6 m/s is designed to be lowered down to either 3 m/s or around 1.5 m/s. The above results show that the choice of 3 m/s or 1.5 m/s does not really affect the fire development in a tunnel after activation of such a fire suppression system with the designed capacity. The main reason is that the flame spread along the fuel surface after activation of the suppression system was mostly suppressed in these tests, as shown in Appendix I.

From the perspective of fire development, the ventilation has limited influence during the range of 1.5 m/s and 3 m/s for the fire suppression systems discussed here.

7.2 Fire spread to target

In the test series of design fires [4], fire spread to the target was observed in the free-burn test. However, in all the tests with fire suppression even with a low density of 2.5 mm/min (5 mm/min in full scale), the fire did not spread to the target 1 m from the main fire load (5 m in full scale).

In the full scale Runehamar tunnel fire suppression tests [6, 7], the fire spread occurred in the last test with closely no water droplets discharged. However, in all the tests with fire suppression even with a very later activation of 8 min and a maximum heat release rate of approx. 40 MW, the fire did not spread to the target 5 m downstream from the rear end of the main fire load.

From the theoretical analysis in Appendix I, it is known that prevention of fire spread to target is easier than prevention of flame spread across the fuel surfaces in the main fire load. It could be expected that in most cases a water spray system with water density higher than 5 mm/min (full scale) should be able to prevent the fire spread to a target 5 m away from the main fire load.

The cases discussed above focus on the fire spread due to radiation from upper smoke layer. As discussed in Section 6.3, One special case is a small fire that is inclined by the wind, e.g. a fire with short fuel. In such cases the flame could impinge on the vehicle nearby. Previous fire spread tests carried out in the Törnskog tunnel with 5.5 MW fire and velocity of 5.5 m/s and 3 m/s show that after activation of the suppression system with 5 mm/min fire spread to target was suppressed even when the flame tip touches the target.

Therefore, all the tests with suppression systems show that generally there will be no fire spread after activation of the fire suppression system with such a capacity, and thus no difference in risk for fire spread to target for the change to 3 m/s or 1.5 m/s.
In case that the vehicles are in a queue situation with 3 m/s initially and the vehicles are really so close, it is of course possible for the fire to spread to the vehicle behind. This may occur before the activation of the fire suppression system. However, the difference between the case of keeping or changing to 3 m/s and the case of changing to 1.5 m/s after detection of a fire is very limited as the period from this moment to the time of activation of the suppression system should be short, e.g. 2 min. The change of ventilation itself takes time, mainly depending on the fan capacity, tunnel geometry and location of the fire relative to tunnel portals. Mostly it could take 30 seconds to 1 min or slightly more. Therefore the difference due to the gradual change in velocity is expected to be limited. After activation of the suppression system, such a system should be capable of preventing further fire spread, and therefore there will be no difference for use of different targeted velocities.

In summary, there is only a limited difference between the case of changing to 3 m/s and the case of changing to a lower velocity e.g. 1.5 m/s, after fire detection.

7.3 Toxic gases and visibility

Previous work [5] has shown that after activation of the suppression system, the CO yield increases, while the total production rates of CO are mostly lower than those in the free burn tests as in most tests the fire suppression systems were activated early and efficient suppression was achieved.

In this section, results with CO and visibility obtained from the toxicity tests are presented. In the analysis of effect of ventilation on toxic gases and visibility in tunnels with suppression systems, the tests chosen for comparison have similar heat release rates at the activation. The purpose is to check whether the ventilation has significant influence on the toxic gas concentration and yield, and visibility before and after activation of the suppression system. Note that the CO production rate can be used for estimation of average CO concentration at downstream, while the CO concentration and visibility at a measuring point can only be used as indicators of environment near downstream of the fire.

7.3.1 Wood pallet fires

Comparison of the CO concentration at mid tunnel height in the fire suppression tests with 1.5 m/s and 3 m/s are shown in Figure 16. The velocities at full scale are 3 m/s and 6 m/s respectively. The corresponding heat release rate curves can be found in Figure 13. In both tests the maximum heat release rates are around 750 kW, while the fire with 3 m/s develops more rapidly in the growth period.

It is shown in Figure 16 that the CO concentrations under 1.5 m/s and 3 m/s are at the same level before activation of the suppression system. Both curves show an increase to around 0.011 % (110 ppm) after activation of the suppression system. After 11 min, CO concentration in the test with 3 m/s is lower probably due to the fact that the heat release rate at this moment is also lower than that with 1.5 m/s.
Figure 16  CO concentration in fire suppression tests for 1.5 m/s and 3 m/s (Wood pallet fires).

Comparison of CO production rates in the fire suppression tests with 1.5 m/s and 3 m/s, respectively, are shown in Figure 17. It is shown that the CO concentrations under 1.5 m/s and 3 m/s are at the same level before and after activation of the suppression system.

Figure 17  CO production rates in suppression tests for 1.5 m/s and 3 m/s (Wood pallet fires).

Comparison of CO yields in the fire suppression tests with 1.5 m/s and 3 m/s respectively are Figure 18. It is shown that the CO concentrations under 1.5 m/s and 3 m/s are at the same level before activation of the suppression system. However, after 4 min the CO yield in the test with 3 m/s increases and becomes higher than that with 1.5 m/s. The main reason could probably be that the fire in test with 3 m/s was suppressed earlier. According to the previous analysis of test data [5], it is known that the CO yield increases rapidly when the fire is close to extinguishment.
7.3.2 PE crib fires

Comparison of CO concentration at mid tunnel height in the fire suppression tests with 0.75 m/s, 1.5 m/s and 3 m/s are shown in Figure 20. The corresponding heat release rate curves can be found in Figure 14. The maximum heat release rate is around 750 kW while the fire at 0.75 m/s develops slightly more rapidly in the growth period. The maximum CO concentrations at mid tunnel height with 1.5 m/s are much higher than the other two
tests before activation of suppression. After the activation, the CO concentration decreases rapidly with time for all the velocities.

Figure 20  CO concentration at mid-height in fire suppression tests under three velocities (PE crib fires).

Figure 21 shows the CO production rates under three different velocities for PE crib fires. The CO production rates for 1.5 m/s are only slightly higher than that for 3 m/s before and after activation of the suppression system. However, the CO production rates for 0.75 m/s are obviously higher. This indicates that at a velocity of 1.5 m/s more CO was produced. The main reason could be that the fire under 0.75 m/s is slightly vitiated. This may also be partly due to the larger uncertainty for a lower velocity where a smoke stratification could exist. After activation of the suppression system, the CO production rates decrease rapidly with time for all the velocities.

Figure 21  CO production rates in fire suppression tests under three velocities (PE crib fires).

Figure 22 shows the CO yields in the fire suppression tests under three different velocities. Similar trend can be found as in Figure 21. Similarly, there appears to be a tendency of increase in CO yield with decreasing velocities. After activation of the suppression system, the CO yield decreases immediately to the initial level.
Figure 22  CO yield in fire suppression tests under three velocities (PE crib fires).

Figure 23 shows the visibility at mid tunnel height in the suppression tests with three different velocities for PE crib fires. Clearly, it shows that before activation of the suppression system, the visibilities at mid tunnel height are approximately the same. After activation of the suppression system, the visibility for 0.75 m/s and 3 m/s are somewhat higher (better) than for 1.5 m/s, between 3 min and 10 min.

Figure 23  Visibility in fire suppression tests under three velocities (PE crib fires).

7.3.3  PUR crib fires

Comparison of the CO concentration at mid tunnel height in the fire suppression tests with 1.5 m/s and 3 m/s are shown in Figure 24. The corresponding heat release rate curves can be found in Figure 14. The maximum heat release rate is 750 kW for 1.5 m/s and 1.1 MW for 3 m/s.
It is shown in Figure 24 that the CO concentration at mid tunnel height for the two velocities are approximately of the same shape as the heat release rate curves, see Figure 15. Further, the difference between the two curves is limited. This indicates the ventilation has limited influence on CO concentration at mid tunnel height for PUR crib fires with velocities of 1.5 m/s and 3 m/s.

Figure 24  Comparison of CO concentration in fire suppression tests for velocity of 1.5 m/s (Wood pallet fires).

Figure 25 shows the comparison of CO production rates in the fire suppression tests with 1.5 m/s and 3 m/s. The CO production rates for 3 m/s are higher than that for 1.5 m/s. Comparing this curve with the heat release rate curve indicates some increase in the CO production rate at 3 m/s.

Figure 25  Comparison of CO production rates in suppression tests for 1.5 m/s and 3 m/s (PUR crib fires).

Figure 26 shows the CO yields in the fire suppression tests with 1.5 m/s and 3 m/s. The CO yield for 3 m/s is slightly higher than that for 1.5 m/s.
Figure 26  Comparison of CO yield in suppression tests for 1.5 m/s and 3 m/s (PUR crib fires).

Figure 27 shows the visibility at mid tunnel height in the fire suppression tests with 1.5 m/s and 3 m/s. Clearly, the difference between the two cases is limited, indicating a small influence of ventilation. Note that in theory the average visibility should be higher with 3 m/s. The reason is that the visibility at the measurement location is close to the fire site, and thus depends on not only ventilation but also on the possible stratification which although is not expected at a location far downstream.

7.3.4 Short summary

In this section, toxic gases and visibility in tests with three different fuel types under different ventilation conditions are compared. It should be mentioned again that the CO production rate can be used for estimation of average CO concentration at downstream,
while the CO concentration and visibility at a measuring point can only be used as indicators of environment near downstream of the fire. Further, the CO production rates and CO yields are estimated based on only three gas analyses at the measurement stations downstream of the fire, and thus some uncertainties need to be considered in analysing the results.

For a location far downstream of the fire site, the CO production rate could be most representative in terms of toxic gas despite the uncertainty of estimation. The comparisons show that before and after activation of the suppression system, the influence of ventilation velocity between 1.5 m/s (3 m/s in full scale) and 3 m/s (6 m/s in full scale) on the CO production rate is mostly insignificant. However, for PE crib fires the CO production rates are much higher at 0.75 m/s (1.5 m/s in full scale). This indicates that at 0.75 m/s the average CO concentration far downstream will be much higher than the other two velocities. The main reason could that the fire was slightly vitiated under 0.75 m/s. Further, some uncertainties in estimation of CO production rate due to existence of stratification needs to be taken into account.

For the CO concentration and visibility at mid tunnel height in the near field of the fire (30 m downstream), the difference between various velocities is mostly insignificant. However, for both wood pallet fires and PE crib fires, velocity of 3 m/s corresponds to a better scenario compared to that with 1.5 m/s. While for PUR crib fires, the case with 1.5 m/s is slightly better. For PE crib fires, results with velocity of 0.75 m/s are similar to that with 3 m/s, i.e. better than those with 1.5 m/s at 30 m downstream.

### 7.4 Summary

Fire suppression systems with side spray nozzles and a water density of 10 mm/min are able to effectively suppress the fire development after activation of the suppression system. Although higher ventilation has more potential to compete with the suppression system, the test results show insignificant effect of ventilation on fire development after the activation. This could be largely due to the effectiveness of the system. If the water density is much lower or the effectiveness of the system is lower, the ventilation effect may be more significant. The fire development strongly depends on the activation time. The recommendation is therefore to detect and identify the fire, and activate the suppression system as early as possible. In the case of most interest, the initial velocity of around 6 m/s is designed to be lowered down to either 3 m/s or around 1.5 m/s. The choice of 3 m/s or 1.5 m/s does not really affect the fire development in a tunnel after activation of such a fire suppression system with the designed capacity. From the perspective of fire development, the ventilation has limited influence during the range of 1.5 m/s and 3 m/s after activation of the fire suppression systems discussed here.

After activation of the suppression system, influence of ventilation on toxic gas production is mostly not significant. Generally a low velocity could cause an increases in CO yield and CO production rate, especially for PE fires. Moreover, for a location far downstream of the fire site, the average CO concentration with a lower velocity is expected to be higher and the visibility becomes lower. Therefore, from the perspective of toxic gas production and visibility, a higher velocity is preferred.

Before activation of the suppression systems, a higher velocity e.g. 3 m/s corresponds to a slightly higher risk for fire spread to nearby vehicles. However, fire spread tests showed that after activation of the suppression system with 10 mm/min, fire spread to target nearby was suppressed even for small fires with flame tip touching the target and for large fires with a target 5 m downstream and a heat release rate of 40 MW. Therefore after activation of the suppression systems, the risk for fire spread is significantly reduced.
and the influence of ventilation is expected to be insignificant. This is especially when the transition from a high velocity to a low velocity is short.

Overall, higher ventilation velocities are preferred in tunnels with fire suppression systems, mainly to reduce the toxic gas production and toxic gas concentration and to increase the visibility. Therefore a slightly high value for velocity is recommended, e.g. 3 m/s instead of 1.5 m/s. However, a velocity of 6 m/s is not recommended as rapid flame spread inside the main fire load is still possible within a certain time after activation of the suppression system.

If the fire suppression system has a lower capacity or the effectiveness of the system is lower, the effect of ventilation will be more significant.
8 Conclusions

In fires without water-based fire suppression systems, the fire growth rate increases linearly with ventilation velocity. Windbreaks reduces the fire growth rate by reducing the local velocities inside the fuel load. To reduce the heat release rate and also maintain certain smoke stratification at the early stage of evacuation, use of a low velocity is preferred. This is specifically important in the case of a queue situation. A lower velocity results in a smaller fire size, improved stratification and lower risk for fire spread to nearby vehicles. Higher velocities increase fire size, destroy downstream stratification and increase risk for fire spread.

The use of a low velocity between 1.5 m/s and 3 m/s at the early stage of evacuation is preferred. How the velocity should be adjusted depends on whether upstream backlayering is allowed and how long it is if so. This is related to the traffic situations and evacuation strategies for the tunnels. In case of no queue formed downstream of the fire in a normal multiple lane uni-directional road tunnel, a velocity of approximately 3 m/s is preferred to control backlayering. However, in case of a queue formed downstream of the fire, a velocity between 1.5 m/s and 2 m/s is recommended. This will reduce the risk for fire spread and improve initial evacuation conditions. At the fire fighting stage, a velocity slightly greater than the critical velocity (3 m/s - 3.3 m/s for most road tunnels) is preferred, to prevent any backlayering and to reduce the concentration of toxic gases and improve visibility far downstream.

Water-based fire suppression systems with side spray nozzles and a water density of 10 mm/min are able to effectively suppress the fire development after activation of the suppression system. Although higher ventilation has a potential to compete with the suppression system, the test results show insignificant effect of ventilation on fire development after the activation. The fire development strongly depends on the activation time. Therefore it is recommended to early detect and identify the fire, and to activate the suppression system. From the perspective of fire development, the ventilation has limited influence during the range of 1.5 m/s and 3 m/s after activation of the fire suppression systems with the designed capacity. Influence of ventilation on toxic gas production after activation of the suppression system is not very significant but generally a low velocity could cause increases in CO yield and CO production rate. Moreover, for a location far downstream of the fire site, the average CO concentration with a lower velocity is expected to be higher and the visibility becomes lower. Therefore, from the perspective of toxic gas production and visibility, a higher velocity is preferred. From the perspective of fire spread to nearby vehicles, after activation of the suppression systems, the risk for fire spread is significantly reduced and the influence of ventilation is expected to be insignificant. This is especially when the period of transition from a high velocity to a low velocity is short. Overall, a slightly higher ventilation velocity, e.g. 3 m/s, is preferred in tunnels with fire suppression systems, with the main purpose to reduce the toxic gas concentration and increase visibility. However, a velocity of 6 m/s is not recommended as rapid flame spread is still possible within a certain time after activation of the suppression system.

If the fire suppression system has a lower capacity or the effectiveness of the system is lower, the effect of ventilation could be more significant.

For design of ventilation systems, it should be kept in mind that if the same fans are operating during the whole fire period, the tunnel velocity obtained generally decreases with increasing heat release rate due to the increasing flow resistance caused by hot gases. Further, tunnels with large slopes should be paid special attention as the buoyancy force may be significantly larger than what is expected when a fire occurs in its vicinity.
9 References

10 Appendix I - Theoretical considerations – fire suppression

A schematic drawing of fire development under wind is shown in Figure 28. The fuels are divided into three regions: initial burning region (region 1), flame spreading region (region 2) and target (region 3).

![Figure 28 A schematic drawing of the fire development in a tunnel under wind.](image)

10.1 Initial burning region

10.1.1 Before activation

Burning of the fuels in this region is assumed to be in the quasi-steady state. The heat release rate can be expressed as follows:

\[
\frac{d\dot{Q}_{1,0}}{dt} = \Delta H_c \frac{d\dot{m}_{f,1,0}}{dt} = 0
\]

(6)

Alternatively, the quasi-steady state mass burning rate per unit area can be expressed as:

\[
\dot{m}_{f,1,0}^* = \frac{\dot{q}_{f 1}^*}{L_g}
\]

(7)

where the net heat flux, \( \dot{q}_f^* \), is:

\[
\dot{q}_{f 1}^* = \dot{q}_f^* + \dot{q}_c^* - \dot{q}_{loss}^*
\]

It may be assumed that the fraction of radiation to the fuel surfaces in the local heat release rate, \( \varphi \), is constant. Therefore, the radiative heat from the flames and smoke, \( \dot{q}_f^* \), is:

\[
\dot{q}_f^* = \varepsilon_f \varphi \dot{m}_f^* \Delta H_c
\]

(8)

The convective heat flux from the flame to the fuel surface, \( \dot{q}_c^* \), is:

\[
\dot{q}_c^* = h_c \Delta T_{f-f}
\]

(9)
The heat loss, \( q'_{\text{loss}} \), consists of two parts: radiative heat loss to the surroundings and conduction heat loss to inner side of the fuel, which can be expressed as follows:

\[
q'_{\text{loss}} = \varepsilon_f \sigma T_f^4 + h_k \Delta T_{f-o}
\]  

(10)

Therefore the energy equation could be expressed as follows:

\[
\dot{m}_{f10}^* (\varepsilon_f \varphi \Delta H_c - L_g) + \dot{q}_c^* - \dot{q}'_{\text{loss}} = 0
\]  

(11)

In the above equations, \( \dot{Q} \) is heat release rate (kW), \( t \) is time (s), \( \dot{m} \) is fuel burning rate (kg/s), \( \dot{m}^* \) is fuel burning rate per unit area (kg/m\(^2\)s), \( \dot{q}_f^* \) is the neat heat flux on the fuel surface (kW/m\(^2\)), \( \dot{q}_F^* \) is the radiation from flame and smoke (kW/m\(^2\)), \( h_k \) is conductive heat transfer coefficient accounting for the heat loss from the pyrolysis region to the preheating region beneath (kW/m\(^2\)K), \( \Delta H_c \) is heat of combustion (kJ/kg), \( L_g \) is heat of pyrolysis (kJ/kg), \( \Delta T \) is temperature difference (K), \( \varepsilon \) is emissivity. Subscript \( c \) is convective, \( f \) is fuel surface, \( F \) is flame, \( loss \) is heat loss, \( 1 \) is initial burning region, \( 0 \) is initial condition before activation of suppression, or ambient condition.

**10.1.2 After activation of the suppression system**

Previously many researches focused on the critical water flow rate to extinguish wood crib fires, corresponding an infinite operation time. A review of these researches is given in reference [2]. These critical values obtained are very low and in fact of limited use in our cases, and therefore they are ignored in the following. To effectively suppress the fire, the water flow rate needs to be much higher.

After activation of the suppression system, the water droplets affect the burning. The water density could be so high that the fire is immediately extinguished on a surface. But for a surface sustaining burning after activation of the suppression system, the heat release rate can be expressed as follows:

\[
\frac{d\dot{Q}}{dt} = \Delta H_c \frac{d\dot{m}_{f1}}{dt} = 0
\]  

(12)

The mass burning rate per unit area can be expressed as:

\[
\dot{m}_{f1}^* = \frac{\dot{q}_F^* + \dot{q}_c^* - \dot{q}'_{\text{loss}} - \dot{m}_w^* L_g}{L_g}
\]  

(13)

It is also assumed here that the radiation fraction to the fuel surfaces, \( \varphi \), is constant. Therefore we get:

\[
\dot{m}_{f1}^* (\varepsilon_f \varphi \Delta H_c - L_g) + \dot{q}_c^* - \dot{q}'_{\text{loss}} - \dot{m}_w^* L_g = 0
\]  

(14)

For a surface sustaining burning, the reduction in burning rate before and after activation of the suppression system could be estimated by:
\[ \dot{m}_{f,1}^{n} - \dot{m}_{i}^{n} = \frac{L_{v,w}}{L_{g}} \dot{m}_{w}^{n} \]  

(15)

where \( L_{v,w} \) is heat of vaporization of water and \( \dot{m}_{w}^{n} \) is water density (l/min or mm/min).

The difference in reality could be underestimated to some extent, as after activation of the suppression system the radiation heat could be reduced significantly although the heat loss also decreases somewhat.

This indicates that the heat release rate immediately jumps to a lower level and remains there after activation of the suppression system. Further, the burning rate is directly proportional to the decreasing water flow density.

At the activation time, the net heat flux excluding the water evaporation equals the initial net heat flux, that is:

\[ \dot{q}_{f,1}^{*} = \epsilon_{f} \varphi \dot{m}_{f,1}^{n} \Delta H_{c} + h_{v} \Delta T_{F-F} - \epsilon_{f} \sigma T_{f,0}^{4} - h_{v} \Delta T_{F-F} = \dot{m}_{f,1}^{n} L_{g} \]  

(16)

For immediate suppression of burning on a fuel surface, the energy equation at the critical condition could be expressed as:

\[ \dot{q}_{f,1}^{*} - \dot{m}_{w}^{n} L_{w} = 0 \]  

(17)

or

\[ \dot{m}_{f,1}^{n} L_{g} - \dot{m}_{w}^{n} L_{w} = 0 \]  

(18)

Therefore, the critical condition for immediate and effective suppression or extinction of the burning in this region can be simply expressed as follows:

\[ \dot{m}_{w}^{n} = \frac{L_{v,w}}{L_{f,1}} \dot{m}_{f,1}^{n} \]  

(19)

Here we only consider the water density arriving at the fuel surfaces. This water density for effective suppression is shown in Figure 29 as a function of the initial fuel burning rate.

![Figure 29](image)

**Figure 29**  Critical water density for immediate suppression, assuming heat of pyrolysis of 1.5 MJ/kg for fuel and heat of vaporization of 2.6 MJ/kg for water.
Some estimations are made here based on the above figure. For wood, the initial fuel burning rate is around 10 g/m$^2$s, corresponding to critical water flow rate of around 6 g/m$^2$s. For Polystyrene the initial fuel burning rate is around 35 g/m$^2$s, corresponding to critical water flow rate of around 20 g/m$^2$s. For Polyethylene the initial fuel burning rate is around 20 g/m$^2$s, corresponding to critical water flow rate of around 12 g/m$^2$s. Note that the realistic values slightly differ from the estimated ones due to slight difference in heat of pyrolysis for various fuels.

The above graph can also be plotted as follows in form of net heat flux, see Figure 30.

![Figure 30](image)

**Figure 30** Water density for Immediate suppression as a function a net heat flux.

The above equation correlates the initial heat release rate to the critical water flow rate for effective suppression of burning for different fuels. It could be used for indications of the variance of critical water flow rate with different fuel types.

Note that in the above analysis, the water density applies to all the burning surfaces rather than the top of burning item or the horizontal tunnel area.

In a real fire, the water penetrates into or moves from surface to surface to the deep region of a three-dimensional fuel. Therefore, it could take a long time for the water to take effect. The fire therefore could continue to increase in size during a certain period after activation of the suppression system. Besides, the water droplets evaporate during the traveling to the fuel surfaces, which indicates the initial water density needs to be greater to compensate for these losses.

### 10.2 Spreading region

Pilot ignition is the key mechanism of flame spread inside the main fuel load in tunnel fires. Compared to spontaneous ignition, the net heat flux required for ignition is less. This can be interpreted to the fact that a lower ignition temperature is required for ignition. Typically, pilot ignition temperature is 100 to 200 °C lower than spontaneous ignition temperature which is around 500 °C e.g. for wood.

In the following analysis, the cases with no windbreaks are considered. If there are windbreaks especially the front windbreak, the ventilation conditions in the main fire load
will be very different and the effect of tunnel ventilation on fire development could be reduced significantly.

### 10.2.1 Before activation

According to the previous work [1], the fire growth rate in the spreading region is:

\[
\frac{d\dot{Q}_{2,0}}{dt} = w_p \eta \dot{m}_{f,2,0}^* \Delta H_c \frac{\dot{q}_{f,2}^* \Delta}{(k \rho c)(T_{ig} - T_o)} \propto \frac{w_p \eta \dot{m}_{f,2,0}^* \Delta H_c}{(k \rho c)} u_o \propto C_f w_p u_o \tag{20}
\]

where the material property, \( C_f \), is defined as:

\[
C_f = \frac{\dot{m}_{f}^* \Delta H_c}{k \rho c}
\]

and the net heat flux on the surface is:

\[
\dot{q}_{f,2}^* = \varepsilon_f \dot{q}_{inc}^* + h_c \Delta T_{F-f} - \varepsilon_f \sigma T_{ig}^4 - h_k \Delta T_{f-o}
\]

So the fire growth rate could be very sensitive to the change in the heat fluxes.

In the above equations, \( w_p \) is wet perimeter of the fuels at one cross section (m), \( \eta \) is combustion efficiency, \( c \) is heat capacity (kJ/kgK). Subscript 2 indicates the spreading region, i.e. region 2.

### 10.2.2 After suppression

For a surface that continues to spread along the surface after activation of the suppression system, the fire growth rate in the spreading region can be expressed as:

\[
\frac{d\dot{Q}_{2}}{dt} = w_p \eta \dot{m}_{f,2}^* \Delta H_c \frac{(\dot{q}_{f,2}^* - \dot{m}_{w}^* L_{v,w})^2 \Delta}{(k \rho c)(T_{ig} - T_o)} \tag{21}
\]

The above equation could be expressed as follows:

\[
\frac{d\dot{Q}_{2}}{dt} \propto C_f w_p u_o - f(\dot{m}_{w}^* L_{v,w}) = \frac{d\dot{Q}_{2,0}}{dt} - func(\dot{m}_{w}^* L_{v,w}) \tag{22}
\]

where \( func \) is a function. This indicates that the fire growth rate decreases with the increasing water flow rate.

The critical condition for immediate suppression of flame spread in the spreading region, i.e. no flame spread, could be expressed as:

\[
\dot{q}_{f,2}^* - \dot{m}_{w}^* L_{v,w} = 0 \tag{23}
\]

or
Note that in the initial burning region, the radiation flux comes from flames right above the surface and the external flames and smoke, while in the spreading region, the radiation flux mainly comes from the flame and smoke upstream. The heat flux \( q_{f, 2}^* \) is therefore less than \( q_{f, 1}^* \). Although previously it was assumed that the burning reaches quasi-steady state immediately, the burning in the spreading region takes some time to reach this state in reality. Therefore the heat flux in the spreading region (flame fronts) is mostly lower than that in the initial burning region. This indicates that to suppress the fire within a certain time, less water is required to prevent fire spread than suppression of burning in the initial burning region.

Note that if the water flow rate is high enough, the net heat flux term could become negative, i.e., :

\[
q_{f, 2}^* < \dot{m}_{*w}^* L_{v, w}
\]

Therefore the flame spread could be suppressed completely, i.e., :

\[
\frac{dQ}{dt} = 0
\]

10.3 Fire spread to target

The main spread occurs on the exposed surfaces of the target, mostly on the top surfaces at the edge nearby the main fire load.

Radiation heat transfer and spontaneous ignition are considered as two key mechanism of fire spread in a tunnel fire. It has been found that to ignite such a target, the incident heat flux normally needs to exceed around 20 kW/m\(^2\) [13]. In case of fire suppression, the correlation for ignition of a target can be expressed as follows:

\[
\dot{Q}^{*}_{\text{inc}} - \dot{m}^{*}_{w} L_{v, w} \geq \dot{q}_{cr}^{*} = 20 \text{ kW/m}^2
\]

The critical water flow rate for prevention of fire spread to target is plotted as a function of incident heat flux in Figure 31. It is assumed that the heat of pyrolysis is 1.5 MJ/kg for the fuel and the heat of vaporisation is 2.6 MJ/kg for water. It can be found that the water density required to prevent fire spread is e.g. 0.7 mm/min for an incident heat flux of 50 kW/m\(^2\).

The basic energy equation in fact is:

\[
\dot{q}^{*}_{\text{net}} = \varepsilon (\dot{q}^{*}_{\text{inc}} - \sigma T_{w}^4) + \dot{q}^{*}_{c} - \dot{m}^{*}_{c, \text{min}} L_{c} - \dot{m}^{*}_{w} L_{v, w} > 0
\]

The above equation is similar to the heat flux equation in the spreading region. However, in the spreading region, the incident heat flux mainly comes from flame radiation, indicating a higher level than the fire spread to a target. Further, spontaneous ignition is
responsible for ignition in the spreading region, indicating a lower ignition temperature than that for the fire spread to a target. Therefore, it is easier to prevent fire spread to target, compared to suppression of an existing flame in the main fire load (both initial burning and spreading regions).

![Graph](image)

**Figure 31** Critical water density for prevention of fire spread to target, assuming a heat of pyrolysis of 1.5 MJ/kg for fuel and heat of vaporization of 2.6 MJ/kg for water.

The above water density is the water arriving at the target surface. As the target is generally ignited on the top surface first, it can directly be applied to determine the requirement for prevention of fire spread. Compared to the previous graph, it in fact indicates that the water density for prevention fire spread to target is much lower. For example, a net heat flux of 40 kW/m² corresponds to a water density of 0.5 mm/min for suppression of fire spread to target while it is 0.9 mm/min for initial burning region. Note that for initial burning region the value corresponds to all the fuel surface areas while for fire spread to target it only applied to the top surface as it is typically the starting location of a possible fire spread. Therefore in practice, the amount of water required for prevention of fire spread should be significantly lower than that required for suppression of burning in the main fire load.

The lowered heat release rate due to water droplets arriving at the main fuel load surfaces also reduces the risk of fire spread to target. Further, the gas cooling effect above the target and in the vicinity of the main fuel load results in reduction of the gas temperature and incident heat flux. This also prevents the gas phase ignition on the surface that means a higher critical minimum fuel mass burning rate is required for ignition or sustaining burning.

### 10.4 Comparison of water density required for the three regions

At critical condition, the same energy equations apply:

Before activation:
After activation of the suppression system:

$$m_f^* = \frac{\dot{q}_f^*}{L_g} = \frac{\dot{q}_f^* + \dot{q}_c^* - \dot{q}_{\text{loss}}^*}{L_g} = \frac{\alpha(\dot{q}_m^* - \sigma T_f^4) + \dot{q}_c^*}{L_g}$$

(29)

For initial burning region, the incident radiation heat fluxes and convective heat fluxes from flames are highest, indicating that the burning in this region is most difficult to suppress. The radiation loss could be considered to be insignificant compared to the high incident heat flux.

For spreading region, the incident radiation heat fluxes and convective heat fluxes from flame fronts are not so high, and the radiation loss is not very significant compared to the incident heat fluxes as pilot ignition applies.

For target, the incident radiation heat fluxes and convective heat fluxes from flame fronts are not so high, and the radiation loss can be significant compared to the incident heat fluxes as spontaneous ignition applies. Further, the water density discussed here for prevention of fire spread to the target corresponds to the water arriving at the target top surface, while it corresponds to the water arriving at the whole burning surfaces for the main fire load. Therefore, the total amount of water required for prevention of fire spread should be significantly lower than that required for suppression of burning in the main fire load.

Therefore according to the difficulty in suppression, or the magnitude of the critical water flow rate, we can classify the regions by:

**Initial burning region** > **Spreading region** >> **Fire spread to target**

This may indicate that early activation is important, especially if the water flow rate is not high and immediate suppression cannot be achieved.

### 10.5 Global fire growth rate

A schematic drawing of the fire development with suppression systems is plotted in Figure 32.
If the water flow rate is low (\( \dot{q}_{f,2}^* > \dot{m}_w^* L_{v,w} \)), the fire continues to spread (Process 0→1 in Figure 32), and the fire growth rate could be expressed as:

\[
\frac{d\dot{Q}}{dt} = \frac{d\dot{Q}_1}{dt} + \frac{d\dot{Q}_2}{dt} \propto C_f w_{v,p} u_v - f(\dot{m}_w^* L_w)
\]  (31)

This indicates that under this condition the fire growth rate increases with ventilation velocity and decreases with water flow rate. In such cases, suppression systems are not so effective that the flame continues to spread after activation of the suppression system and that finally the whole fuel burns out. Fire spread to a target may occur if the water flow rate is low.

If the water flow rate is higher (\( \dot{q}_{f,2}^* < \dot{m}_w^* L_{v,w} \)), the flame spread in the spreading region could be suppressed but the burning continues in the initial burning region (Process 0→2 in Figure 5), the fire growth rate can be expressed as:

\[
\frac{d\dot{Q}}{dt} = 0
\]  (32)

This indicates that under this condition the heat release rate is constant as neither flame spread in the spreading region nor fire spread to target occurs.

Or if the fire is completely extinguished (\( \dot{q}_{f,1}^* \leq \dot{m}_w^* L_{v,w} \), Process 0→3 in Figure 5), the fire growth rate can be expressed as:

\[
\frac{d\dot{Q}}{dt} = 0
\]  (33)

The heat release rate could be expressed as follows:

\[
\dot{Q} = 0
\]  (34)
The effect of ventilation on the effectiveness of a suppression system is clear. If the flame spread in the spreading region is suppressed or if the fire is extinguished, the ventilation has closely no influence on the performance of suppressions system. However, if the flame spread is not suppressed, the fire continues to burn and the fire growth rate increases with ventilation velocity.

The above theoretical analyses, however, differs from a realistic fire with a suppression system in a tunnel. In comparison to Figure 32, a more realistic drawing of the fire development with suppression systems is shown in Figure 33. A suppression system takes effect with a delay, mainly due to the complexity of the fuel bed and the interaction of water droplets with fire plume. Therefore in most cases, the heat release rate curve is continuous without a sharp drop.

![Figure 33](image)

**Figure 33** Schematic drawing of the fire development with suppression systems (realistic fires).

To determine the effectiveness of a suppression system, criteria needed to be defined. According to the above analyses, it is clear that the main criteria that could be used is whether the flame spread in the spreading region is suppressed or not. In theory, if the flame spread is suppressed, the heat release rate after activation of the suppression system will decrease with time, and thus lower than that at the activation time. The fuel consumed during a fire is also limited to the initial burning region. In real cases both the heat release rate and the fuel consumed could be somewhat higher than the theoretical values, but the criteria could still be applied. Therefore to determine whether a fire is suppressed or not, the criteria could be defined as follows:

1. The heat release rate after activation of the suppression system is not much greater than (or at the same level e.g. max 20% higher) that at the activation time;

2. The fuel (or energy content) consumed after activation of the suppression system in a fire to that in a free burn fire is less than a given value e.g. 20 %.

The use of these definitions are useful only if the systems are activated at the early stage of a fire (fire growth period). If the heat release rate has already approached the peak value, the use of the first criteria is invalid, and instead the second criterion is more realistic and logical.
10.6 Actual water flow rate

In the above analyses, the water droplets arriving at the fuel surfaces are discussed. There is a need to correlate this water flow rate to that discharged from a fire suppression system (nozzles).

The actual water flow rate arriving at the fuel surfaces could be estimated by the following expression:

\[ \dot{m}_w = K_w K_p \dot{m}_{w,s} \]  \hspace{1cm} (35)

or

\[ \dot{m}_w^* = K_w K_p \dot{m}_{w,s}^* \]  \hspace{1cm} (36)

where is \( K_w \) the physical factor, \( K_p \) is the penetration factor. Subscript \( s \) means fire suppression system or nozzles.

The physical factor \( K_w \) is defined as:

\[ K_w = K_v K_c K_u \]  \hspace{1cm} (37)

where \( K_v \) is the view factor between a specific fuel and nozzles, \( K_c \) is the percentage of the amount of water droplets that fall directly through the openings of the fuel bed in the total amount of water droplets that reaches the vicinity of the fuel surfaces, \( K_u \) is a correction factor that accounts for the discharging behavior. The view factor \( K_v \) can be estimated based on the solid angle and it should be in a range of 0 and 1. \( K_c \) is also in a range of 0 and 1 with 1 indicating that no water droplet leaves the fuel bed directly, i.e. all falls onto the fuel surfaces. The factor \( K_u \) in fact is the ratio of the actual amount of water droplets onto the surface to the average amount of water droplets discharged in the view angle for uniformly discharged nozzles. By default, it may be assumed that a full cone nozzle discharges water droplets uniformly throughout the cone. Or else, for a higher density in the view angle a value greater than 1 should be set. For example, if a nozzle is placed right above the fuel bed such as 5 cm above, the factor \( K_v \) can be set to 1. If all the water droplets do not fall through the fuel bed, the factor \( K_u \) should be 1. If the nozzles can be assumed to discharge uniformly across the cone, the factor \( K_u \) is 1. Clearly, all these factors are physical parameters. They are only dependent on the relative configurations of the fuel and the nozzles, and the discharging properties of the nozzles. This indicates that even with a same water density, suppression systems of different configuration will have different performances in case of a tunnel fire.

The penetration factor \( K_p \) is the percentage of water droplets discharged in the view angle that survives on the way to the fuel surfaces. So it is mainly dependent on the evaporation rate in the path. The distance between the nozzle and the fuel bed is a key parameter for the factor \( K_p \). If a significant amount of smoke flow exists between the nozzle and the fuel bed, cooling of the water droplets cannot be ignored and thus this factor should be lower than 1. It has been found that this factor is related to the water flow rate and the convective heat flow [14]. As it depends on the local environment, it is in most cases cannot be estimated simply. However, for side sprinklers installed close to the fuel bed in tunnels it could be reasonably assumed that the factor is close to unit.

After activation of the suppression system, some water droplets could take a long time to reach the initial burning region by surface flowing. Therefore the physical factor \( K_w \) could increase with time.
Our work is concentrated on innovation and the development of value-adding technology. Using Sweden's most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 9000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.