

# A modified critical velocity for road tunnel fire smoke management with dedicated smoke extraction configuration



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## ABSTRACT

Life safety is one of the objectives of fire engineering design for road tunnels. Fire engineering design requires maintaining a tenable condition for a period of time to allow occupants to evacuate to safety. This will be achieved by controlling the smoke under credible design fire scenarios in a tunnel. The critical location in a tunnel fire emergency condition is the tunnel region upstream of the fire, where occupants are most likely to reside as traffic jam can usually be created by the fire incident. Tenability for the downstream region of fire is not the main focus of this research because vehicles can generally drive out of the tunnel at a higher speed than that of the smoke flow, and local damper smoke extraction can help keep a tenable condition in the downstream region beyond the local fire zone, in case there is a congestion in the downstream region of the fire.

To maintain a tenable condition in the upstream tunnel region from the fire incident, the required minimum longitudinal flow velocity to prevent smoke backlayering can be calculated based on NFPA 502 recommendations. This critical velocity takes no credit of the smoke extraction or active overhead fixed fire suppression effects.

Smoke extraction with a dedicated smoke duct along the entire length of the tunnel is gaining popularity because of its efficiency and robustness in providing a tenable environment in the tunnel with unknown upstream and downstream traffic conditions. In this paper, a modified critical velocity to control smoke back-layering while smoke extraction and fire suppression systems are operating has been analyzed. This modified critical velocity is approximately 20% lower than the critical velocity that is recommended in NFPA 502. This allows significant savings on ventilation capacity for road tunnels which have a local smoke exhaust capability using a dedicated smoke duct.

It is concluded that the smoke extraction performance is similar whether using ceiling dampers or vertical wall-mounted dampers for smoke capture to maintain tunnel tenability. However, tunnel gradients play a major role on the modified critical velocity for a nominated design fire and the required smoke extraction rate.

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## Introduction

Tunnel accidents involving a fire incident is a low frequency event. However, its consequence is serious if the fire emergency system is not properly designed and managed to cope with this special event.

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One of the design objectives of a tunnel fire life safety system based on smoke extraction is to maintain tenable conditions in the tunnel and to contain the smoke within a manageable segment of the tunnel, allowing the occupants to be evacuated through the exits or egress passages before developing fire hazards make the tunnel untenable.

When a fire incident happens in a longitudinally ventilated tunnel, two zones will be developed. One is the tunnel zone in the upstream traffic location relative to the fire incident, the other is the downstream traffic location relative to the fire location. In most cases, the downstream zone is of less concern because vehicles can continue to drive away at a higher speed than that of the smoke flows, if there is no traffic congestion in the downstream zone. The local smoke extraction system can also help keep a tenable condition in the downstream section of the tunnel beyond the local fire zone, which means there is less of a concern even if there is traffic congestion in the downstream. However, the upstream zone is the major concern because traffic will build up behind the fire because of the fire incident. Several publications have discussed smoke control to maintain tenable conditions upstream of the fire location [1–9]. However, the impact of smoke extraction and spray water fire suppression on the required critical velocity has not been included in their investigations.

In newly built road tunnels, local smoke exhaust systems with a dedicated smoke duct is gaining popularity because of their effectiveness in mitigating fire hazards developing in the tunnel. For example, the renovated Mont Blanc Tunnel between France and Italy, the Clem 7 tunnel and the Airport Link road tunnel in Brisbane Australia, and the Alaskan Way Viaduct replacement tunnel in Seattle have adopted the concept of a dedicated smoke exhaust duct to ensure the smoke in close proximity to fire incident can be extracted. Tunnel emergency ventilation system design to mitigate fire hazards normally utilizes air flow momentum to effect smoke control with longitudinal flows that establish critical velocity as recommended in NFPA502 for vehicular tunnels [10]. However, this flow capacity does not take into account of the local smoke extraction effects.

In some tunnels in the US, Japan and Australia, a sprinkler or deluge systems are being utilized to actively control the fire spread and protect the tunnel structure. Gas cooling of the hot upper smoke layer is achieved through heat convection, mass transport and evaporative cooling effects as a result of sprinkler spray field created by overhead fixed fire suppression system operation. Unlike tunnels with longitudinal ventilation, when the smoke exhaust and water based sprinkler fire suppression system are operating, this required critical velocity to protect the upstream zone can be reduced when the smoke extraction is enhanced with optimized local damper operation configuration to effectively limit the spread of smoke and untenable conditions within a local tunnel segment.

This paper discusses a modified critical velocity for road tunnels, where a dedicated smoke extraction system and water based fire suppression system is provided. This modified critical velocity and the extraction rate will be determined through a performance based approach considering the specific tunnel ventilation and fire safety provisions of the tunnel. Several critical fire scenarios which should be considered have been highlighted. Two different tunnel gradients have also been analyzed in this paper, and a methodology has been proposed on how to determine the modified critical velocity and the smoke exhaust capacity.

Design parameters such as fire scenarios, fire sizes, tunnel gradient, fire location, smoke extraction location and total number of open smoke extraction dampers are also analyzed to confirm the performance of this modified critical velocity with an evaluation of system robustness of operating modes and configuration.

## Design methodology and parameters

The primary issue for tunnel ventilation design is to determine the required longitudinal ventilation air flow to prevent the smoke back-layering in the upstream, and to determine the required smoke exhaust capacity when a dedicated smoke extraction duct is being considered.

To mitigate fire hazards from a fire incident in a tunnel, the required smoke exhaust flowrate should be determined considering the total air supply through the available makeup airflow openings of the tunnel (i.e. entrance and exit portals). The supply air from these openings, which can be calculated based on the longitudinal flows along the tunnel, will mix with the fire generated smoke and therefore increase the overall smoke volume that is required to be extracted. According to the recommendation of PIARC fire and smoke control [11], a longitudinal ventilation velocity along the road tunnel should be controlled at around 3.0 m/s to avoid smoke backlayering under fire conditions. However, this critical velocity requirement can theoretically be reduced when considering buoyant energy generated by fire is being removed from the tunnel by extraction into a dedicated smoke duct. An initial estimate of the required extraction rate is based on establishing the 3.0 m/s velocity in the longitudinal flow generated from each side of the tunnel fire.

To analyze the modified critical velocity, an example tunnel representing a typical tunnel, as detailed in Table 1, with a dedicated smoke duct provided, has been evaluated. The evaluation incorporates an overhead fixed fire-fighting system (FFFS) [12] configuration consistent with many other system designs (12 mm/min water application rate) throughout the world for managing road tunnel fires.

A smoke exhaust duct with a fixed smoke extraction rate of 282 m<sup>3</sup>/s was established by trial and error study of initial longitudinal airflow from each portal of the tunnel and tunnel air cooling by an overhead FFFS water spray determined with Subway Environment Simulation (SES) modeling of the example tunnel. The tunnel configuration and design parameters relevant to ventilation are listed in Table 1. The example 2-lane tunnel is assumed to have a gradient ranges from –4% to +1.6%,

**Table 1**  
Parameters of tunnel configuration and ventilation system.

| Parameter                               | Value   |
|---|---|
| Tunnel cross section area               | 54 m <sup>2</sup> (2 lane road tunnel)                    |
| Tunnel ceiling height above road        | 5.4 m   |
| Design fire heat release rate (HRR)     | 100 MW [13]   |
| Sprinkler water application rate        | 12 mm/min   |
| Smoke extraction rate                   | 282 m <sup>3</sup> /s (approximately 338.4 kg/s at 20 °C) |
| Spacing of the dampers along the tunnel | 33 m (measured from center to center of the damper)       |
| Effective opening area per damper       | 10 m <sup>2</sup> for vertical dampers                    |
| Spacing of tunnel cross passage doors   | 198 m (measured from center to center)                    |

and the tunnel roof height is assumed to be 5.4 m from the road surface with a cross section area of 54 m<sup>2</sup>. Considering the recent findings from the tunnel fire research in SP [13], the design fire is assumed to be 100 MW.

Fig. 1 illustrates the ventilation scheme incorporating the smoke extraction. As the smoke extraction system is operating, it creates a negative pressure in the tunnel to induce smoke flow towards the exhaust points in the tunnel zone downstream of the fire. Therefore, the upstream longitudinal ventilation velocity that is required to prevent smoke backlayering and push the smoke in the downstream direction (i.e. longitudinal ventilation establishing critical velocity [10]) will be less than that is required for the condition that does not consider the smoke extraction.

Based on above discussion, the critical velocity that takes credit for the combined effects of fire suppression and the smoke extraction is labeled as “the modified critical velocity” in this paper, and its dependency on the other parameters has been investigated with CFD modeling approach.

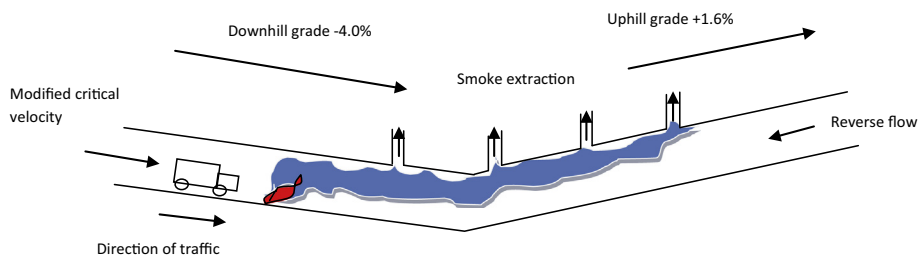
Though this analysis is interested in the steady state results, a bi-linear fire growth curve has been used in this analysis for the convenience of CFD implementation purpose to observe the smoke development and ensure steady state conditions can be achieved. From 0 s to 180 s the fire heat release rate (HRR) grows from 0 MW to 86.8 MW, then grows at 0.92 MW/min to 100 MW. The ambient air temperature is assumed to be 20 °C, and the portal wind effect is not considered for any of the cases to limit the number of variables.

The base case for this analysis, as shown in Fig. 2, considers a +1.6% gradient tunnel segment with longitudinal ventilation without smoke extraction, and assumes sprinkler operation delivers 12 mm/min for a fire zone of 50 m long. No analysis of a case with a zero gradient was undertaken as the purpose was to show the influence on critical velocity of a smoke extraction system.

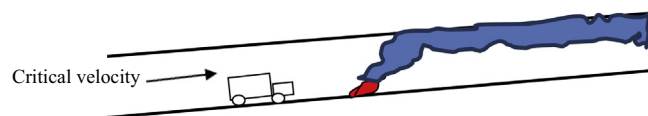
To study the effect of variations of each individual parameter, only one parameter is changed between each case. This rolling baseline scheme, where a single parameter is modified in a simulation case, is used to identify unique impacts of each parameter. Variation sequences for the analyzed cases are summarized in Table 2.

The engineering analysis employed Computational Fluid Dynamics (CFD) modeling techniques to simulate and visualize the smoke flow behavior for the cases described above. Visualization of smoke density and other fire hazards was developed so that the modified critical velocity could be determined from the observation of tunnel flow conditions preventing smoke backlayering for the worst case scenarios.

According to NFPA 502, smoke toxicity, visibility, temperature and thermal radiation are measurable parameters for determining tenability. In this paper, visibility was calculated based on a soot production rate of 0.1 g/g fuel and was



**Fig. 1.** Schematic view of the tunnel fire smoke control system incorporating smoke extraction.



**Fig. 2.** Base case – +1.6% gradient tunnel segment with longitudinal ventilation without smoke extraction.

**Table 2**

Summary of simulation cases developed with rolling baseline scheme.

| Case ID | Case description  |
|---------|---|
| Case A  | Base case: longitudinal ventilation with water spray sprinkler operating, without smoke exhaust. Fire is assumed located at the center of the 2-lane tunnel   |
| Case B  | Based on Case A, add ceiling exhaust with four pairs of remotely controlled roof dampers (each location along the tunnel has two dampers, four pairs of operating dampers in total eight dampers open, each damper has an opening area of 6.4 m <sup>2</sup> ), other parameters remain unchanged |
| Case C  | Based on Case B, replace the ceiling dampers with side wall exhaust using four remotely controlled vertical dampers, other parameters remain unchanged  |
| Case D  | Based on Case C, modify side wall exhaust with three remotely controlled vertical wall dampers, other parameters remain unchanged   |
| Case E  | Based on Case D, modify the gradient from +1.6% uphill to −4.0% downhill, other parameters remain unchanged.  |
| Case F  | Based on Case E, modify the fire location from the tunnel center to the far side from the wall dampers, as shown in Fig. 3, other parameters remain unchanged   |
| Case G  | Based on Case F, include 2 lanes of stopped vehicles with a face area of 2 × 2.0 m <sup>2</sup> upstream of the fire location, other parameters remain unchanged  |

calculated using the formula discussed in the FDS Users Guide [14]. Visibility of 10 m at 2.5 m above the road surface was used as the primary criteria for tenability and a representative marker for other tenability parameters.

### CFD modeling and analysis

Fire Dynamics Simulator (FDS) [14] version 5 developed by the National Institute of Standard and Technology (NIST) was used for the CFD modeling. This CFD software is a fire simulation package where turbulence, combustion, thermal radiation, pyrolysis and water spray can be modeled. During the development process in the past decade, this package has been validated extensively [14,15] and is widely used in fire engineering community for tunnel studies [1–3,7].

The computational domain includes a typical tunnel segment with a dimension of 200 m long, 10 m wide and 5.4 m high, with the corresponding number of mesh cells being 400 × 25 × 27 for CFD modeling. Mesh size is 0.5 m, 0.4 m and 0.2 m for the tunnel length, width and height, respectively. For heat transfer modeling, it is assumed that 30% of the fire generated heat is transferred through thermal radiation. As discussed in the FDS Users Guide [14], the tunnel gradient is implemented through the gravity vector. Open boundary conditions are assumed for the two ends of the tunnel segment that was modeled for this paper.

Table 3 gives an overview of all the cases that have been analyzed. Except for Case A, where there is no extraction, all the other cases listed in Table 3 considered an extraction rate of 338.4 kg/s which is equivalent to an extraction rate of 282 m<sup>3</sup>/s, when assuming an air density of 1.2 kg/m<sup>3</sup> at ambient conditions. This total effective extraction rate achieved at the fire location was calculated based on the critical velocity and the downstream make-up air flow as well as the cooling influence of the sprinklers, and it is the net extraction rate that is achieved with the opened dampers on the wall or ceiling local to the fire. The velocity  $u$  in Table 3 is the velocity which the modeling showed could prevent backlayering. For example, for Case A, modeling at  $u = 3.0$  m/s showed that backlayering could be prevented. The sprinklers are distributed on the ceiling of the tunnel with a spacing of 3 m × 4 m. For a water application of 12 mm/min, each head has a total system discharge flow rate of 144 Liter of water per minute. The sprinkler zone covered 20 m upstream of the fire and 30 m downstream of the fire.

The smoke extraction rate is specified through each damper with a fixed uniform mass flux in kg/s imposed at the faces of each operating dampers. For example, for the case with 4 vertical dampers open, an estimated average airflow speed at the face of the damper is approximately 7–12 m/s depending on the smoke density and temperature.

The following is a discussion of case setup features and smoke control performance observations for each case.

**Table 3**

Summary of tunnel ventilation cases and CFD analysis results.

| Case ID | Exhaust location | Extraction dampers | Fire location              | Gradient (%) | modified critical velocity <sup>a</sup> (m/s) | Figures           |
|---------|------------------|--------------------|----------------------------|--------------|---|-------------------|
| Case A  | NA               | None               | Center                     | +1.6         | $u = 3.0$                                     | Figs. A1a and b   |
| Case B  | Roof exhaust     | 4 Pairs of dampers | Center                     | +1.6         | $u = 2.0$                                     | Figs. A2a and b   |
| Case C  | Wall exhaust     | 4 Dampers          | Center                     | +1.6         | $u = 2.0$                                     | Figs. A3a–c       |
| Case D  | Wall exhaust     | 3 Dampers          | Center                     | +1.6         | $u = 2.0$                                     | Figs. A4a and b   |
| Case E  | Wall exhaust     | 3 Dampers          | Center                     | −4.0         | $u = 2.5$                                     | Figs. A5a and b   |
| Case F  | Wall exhaust     | 3 Dampers          | Far side from wall exhaust | −4.0         | $u = 3.0$                                     | Figs. A6a and b   |
| Case G  | Wall exhaust     | 3 Dampers          | Far side from wall exhaust | −4.0         | $u = 3.0$                                     | Figs. A7a and 10b |

<sup>a</sup> “Modified critical velocity” is the minimum required longitudinal ventilation velocity to prevent backlayering of smoke as observed in CFD modeling analysis.

Case A – No extraction case, centered fire, grade +1.6%

Case A was a reference base case to determine the standard critical velocity that is required to control the smoke back-layering for a tunnel with a grade of +1.6%. The modeling method was based on a longitudinal ventilation system being located far enough from fire so that the upstream cross section velocity field is uniform. Fig. A1a is a plan view showing the fire being located at the center of the 2-lane tunnel. Fig. A1b is an elevation view of smoke visibility of the tunnel centerline, showing an upstream longitudinal ventilation velocity of 3.0 m/s was sufficient to control the smoke backlayering for a tunnel segment with an uphill gradient of +1.6%.

Case B – Roof damper extraction with 4 pairs of dampers open, centered fire, grade +1.6%

Case B was a variation from Case A. The only change is a roof extraction of 338.4 kg/s was implemented with four pairs of roof dampers spaced at 30 m along the tunnel. Fig. A2a shows the location of the roof dampers, which open to extract the smoke from the vehicular tunnel. The objects in Fig. A2a represent the stopped vehicles. Fig. A2b is an elevation view showing the CFD modeling visibility, which confirms that the smoke flows become stabilized after 3 min of fire initiation, and a modified critical velocity of 2.0 m/s can minimize smoke backlayering. This is a significant reduction from the standard critical velocity, as calculated in the Case A where no smoke extraction is implemented.

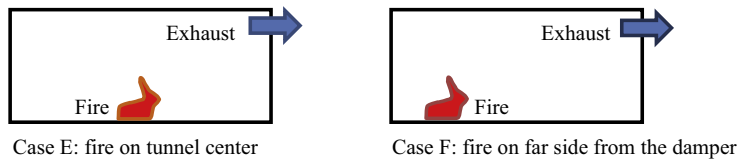


Fig. 3. Case E and Case F with fire location on the tunnel center and far side from the smoke extraction dampers respectively.

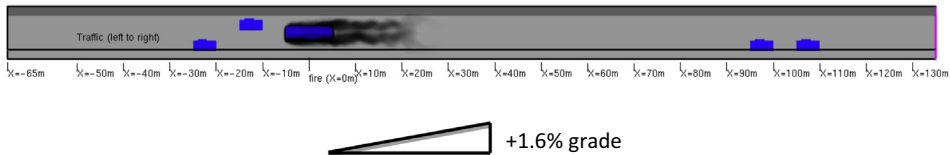


Fig. A1a. Plan view of the fire location for Case A (CFD ID SR99NBjF-19a): No exhaust, longitudinal ventilation  $u = 3.0$  m/s, grade +1.6%.

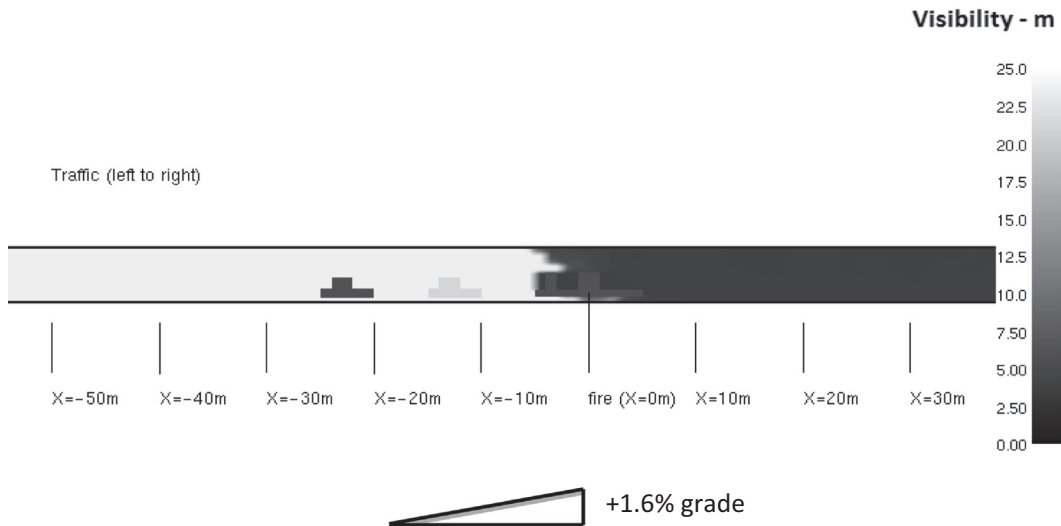


Fig. A1b. Side view of Case A (CFD ID SR99NBjF-19a): No exhaust, longitudinal ventilation  $u = 3.0$  m/s, no backlayering, grade +1.6%.



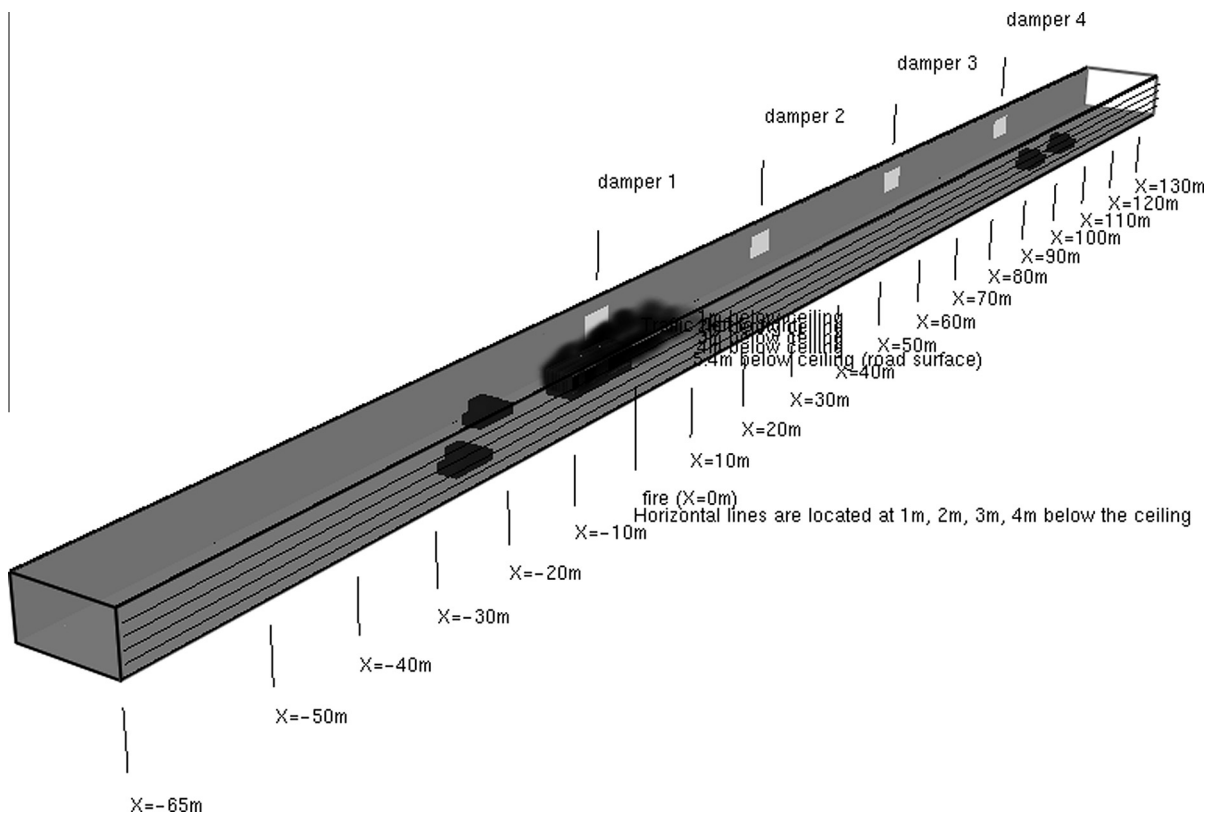
the tunnel roadway center. Fig. A3c shows the modeled smoke visibility, which confirms that a modified critical velocity of 2.0 m/s prevented backlayering. This shows that the performance of the wall dampers is similar to that of the roof dampers for a 10 m wide 2-lane tunnel, the modified critical velocity can be reduced to 2 m/s when compared to the standard critical velocity of 3 m/s.

*Case D – Wall damper extraction with 3 dampers open, centered fire, grade +1.6%*

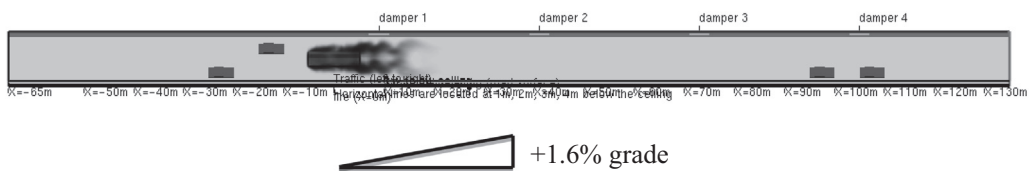
Case D was different from Case C with the number of the opened dampers reduced from 4 to 3, assuming one damper fails in Case D. Fig. A4a shows the location of the opened dampers. Fig. A4b shows that CFD modeled visibility and confirms that modified critical velocity of 2.0 m/s prevented backlayering. Even with only 3 dampers operating, the smoke can still be controlled within approximately 100 m.

*Case E – Wall damper extraction with 3 dampers open, centered fire, grade –4.0%*

Case E was different from Case D with the grade changed from +1.6% uphill to –4% downhill. Fig. A5a shows the damper and fire location. Fig. A5b shows the smoke visibility, and it confirms that a modified critical velocity of 2.5 m/s was required



**Fig. A3a.** A view showing the wall dampers for Case C (CFD ID SR99NBJF-14): Smoke exhaust with 4 wall dampers, longitudinal ventilation  $u = 2.0$  m/s, grade +1.6%.



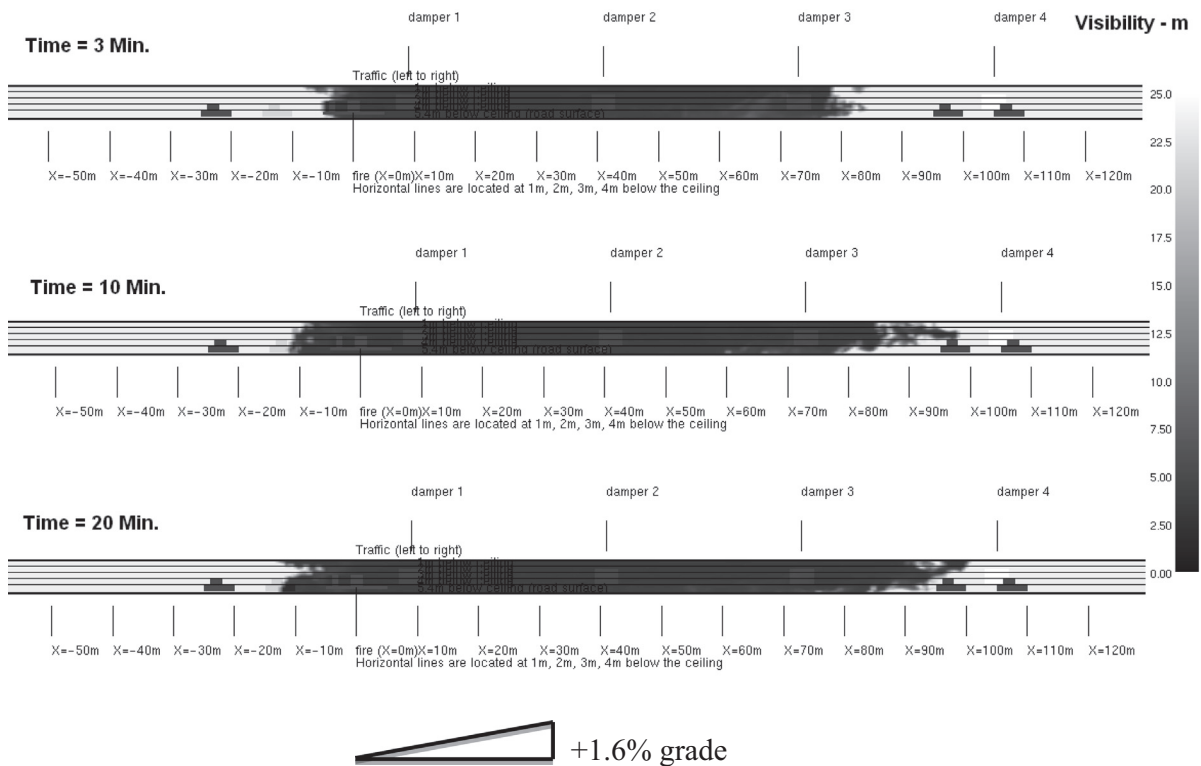
**Fig. A3b.** A plan view showing the fire location for Case C (CFD ID SR99NBJF-14): Location of 4 wall exhaust dampers and fire location, longitudinal ventilation  $u = 2.0$  m/s, grade +1.6%.



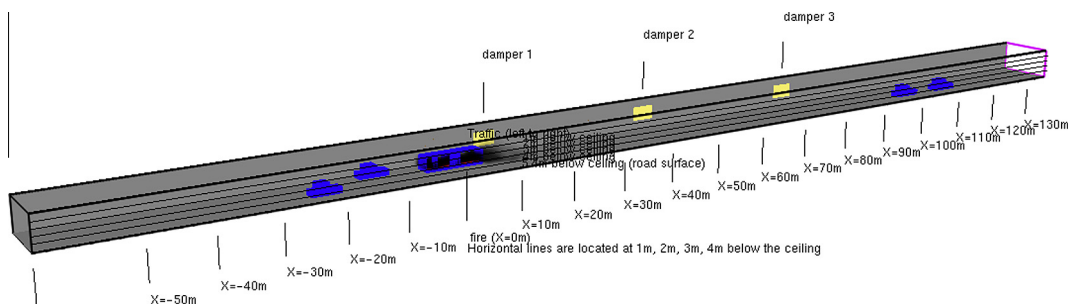
to control backlayering in a tunnel segment with a downhill gradient. The modified critical velocity was increased from 2.0 m/s to 2.5 m/s because the fire location was changed from an uphill –1.6% segment to a downhill –4% tunnel segment. Therefore, additional momentum from the ventilation flow was required to cope with the buoyancy forces developed in fire plume.

*Case F – Wall damper extraction with 3 dampers open, fire on far side of wall damper, grade –4.0%*

Case F was a variation of Case E with a fire located on the far side of the wall from the dampers. The fire was located in the downhill –4% tunnel segment. Fig. A6a shows the location of the fire and the dampers. Fig. A6b shows the visibility field caused by the smoke flow to analyze the influence of the fire locations. Compared to a fire located at the tunnel road center, for a fire on the lane near the tunnel wall that is far from the dampers, as shown in Fig. 3, the required critical velocity to maintain the tunnel visibility and tenability was required to be increased by 20%. Supplemented by smoke extraction, a modified critical velocity of 3.0 m/s can control the smoke backlayering, which is an increase compared to the case with the fire centered in the tunnel roadway.



**Fig. A3c.** CFD predicted centerline visibility after 3, 10, and 20 min for Case C (CFD ID SR99NBJF-14): Smoke exhaust with 4 wall dampers, longitudinal ventilation  $u = 2.0$  m/s, grade +1.6%.



**Fig. A4a.** Case D (CFD ID SR99NBJF-18a): Wall exhaust with 3 dampers, longitudinal ventilation  $u = 2.0$  m/s.



Case G – Wall damper extraction with 3 dampers open, fire on far side of wall damper, grade –4.0%, with stopped upstream traffic

Case G was a variation of Case F, with the upstream traffic blockage effects included. Fig. A7a shows the location of fire, open damper and the stopped vehicles of upstream traffic. The objects in the figure represent the stopped vehicles. Fig. A7b is an elevation view of smoke visibility, which confirms that an upstream airflow velocity of 3.0 m/s can prevent the smoke backlayering for a fire located at the downhill –4% tunnel segment, with stopped traffic in the upstream segment. The stopped traffic blockage in the upstream segment does not make a perceivable difference on the modified critical velocity for this specific scenario. However, if two large trucks with a face area of 6 m<sup>2</sup> each were stopped in the tunnel, this may have marginally greater effect.

**Conclusions**

Based on a typical example 2 lane road tunnel with a fixed smoke extraction rate of 282 m<sup>3</sup>/s, Computational Fluid Dynamics (CFD) analysis has been performed on selected cases to investigate the modified critical velocity considering specific smoke extraction configurations and other parameters. These parameters examined included the extraction damper locations, total number of operating dampers, tunnel gradient, fire location and the traffic blockages in the tunnel region that is upstream of the fire. This analysis has confirmed the following:

- When the smoke exhaust system is operating, the required upstream ventilation velocity to prevent smoke backlayering can be lower than the standard critical velocity that is recommended in NFPA502. For example, for an uphill tunnel gradient of +1.6%, with the local smoke extraction near the fire, the critical velocity can be reduced from 3 m/s to 2 m/s.

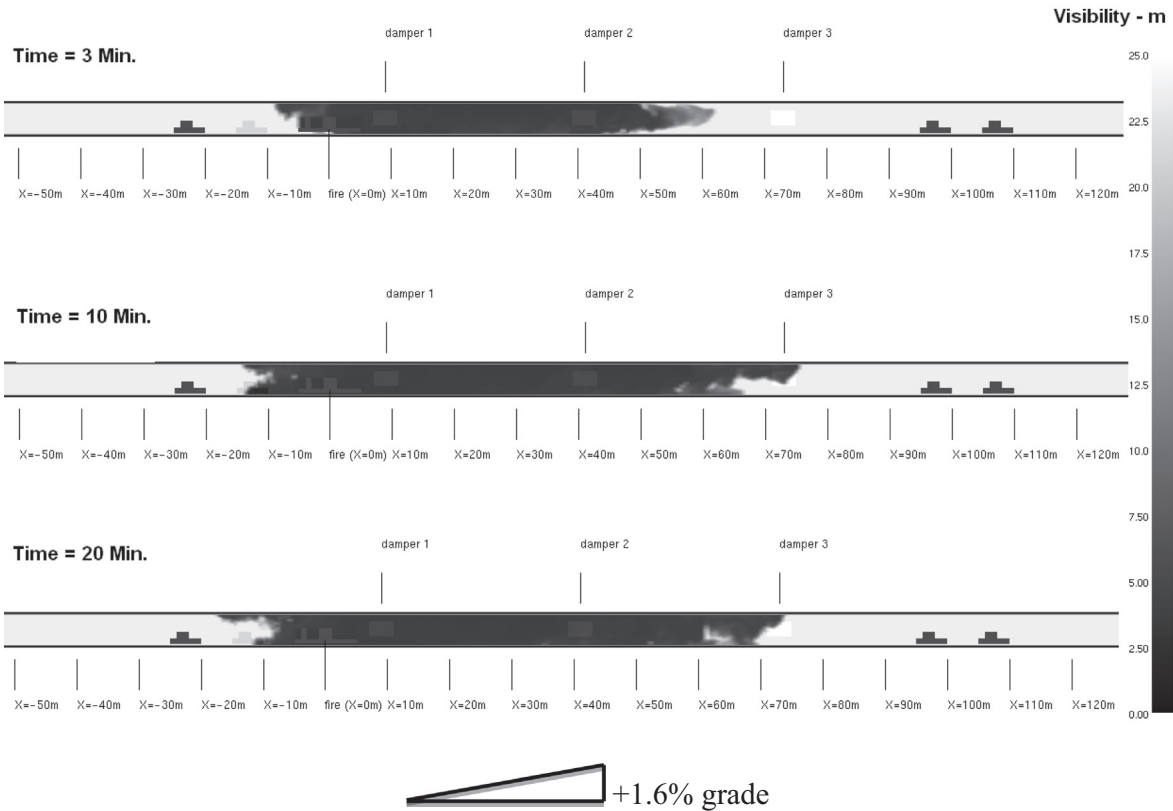


Fig. A4b. FDS predicted centerline visibility after 3, 10, and 20 min for Case D (CFD ID SR99NBjF-18a): Wall exhaust with 3 dampers, longitudinal ventilation  $u = 2.0$  m/s.

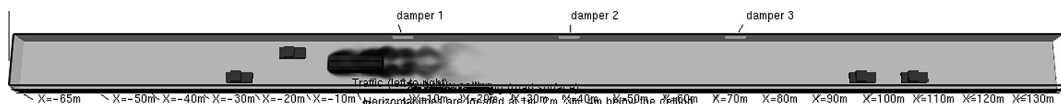


Fig. A5a. Case E (CFD ID Case SR99NBjF-15a): Wall exhaust with 3 dampers, longitudinal ventilation  $u = 2.5$  m/s, gradient –4%.

- For a tunnel width of no more than 10 m, it has been confirmed that the design configuration with vertical side wall dampers and an alternative design configuration with horizontal roof mounted dampers develop equal capabilities to control smoke backlayering and to prevent smoke propagation downstream of the tunnel; the difference in required critical velocity is not significant for these different damper configurations.
- Tunnel gradient plays an important role in establishing the modified critical velocity for a given design fire scenario. A tunnel segment with  $-4\%$  gradient demands a critical velocity of 2.5 m/s, compared to 2.0 m/s for a tunnel with a gradient of  $+1.6\%$ .
- There is no significant impact on the critical velocity created by the number of operating dampers in this investigation. No difference was observed on the demand of critical velocity or the smoke propagation with four wall dampers or three wall dampers.
- Fire location at the far side from the wall dampers requires a higher critical velocity. A critical velocity of 3.0 m/s would be required for a fire located near the wall and on the far side from the wall dampers. This is an increase compared to 2.5 m/s for the case with a fire located in the tunnel center for a tunnel segment with a downhill  $-4\%$  gradient.

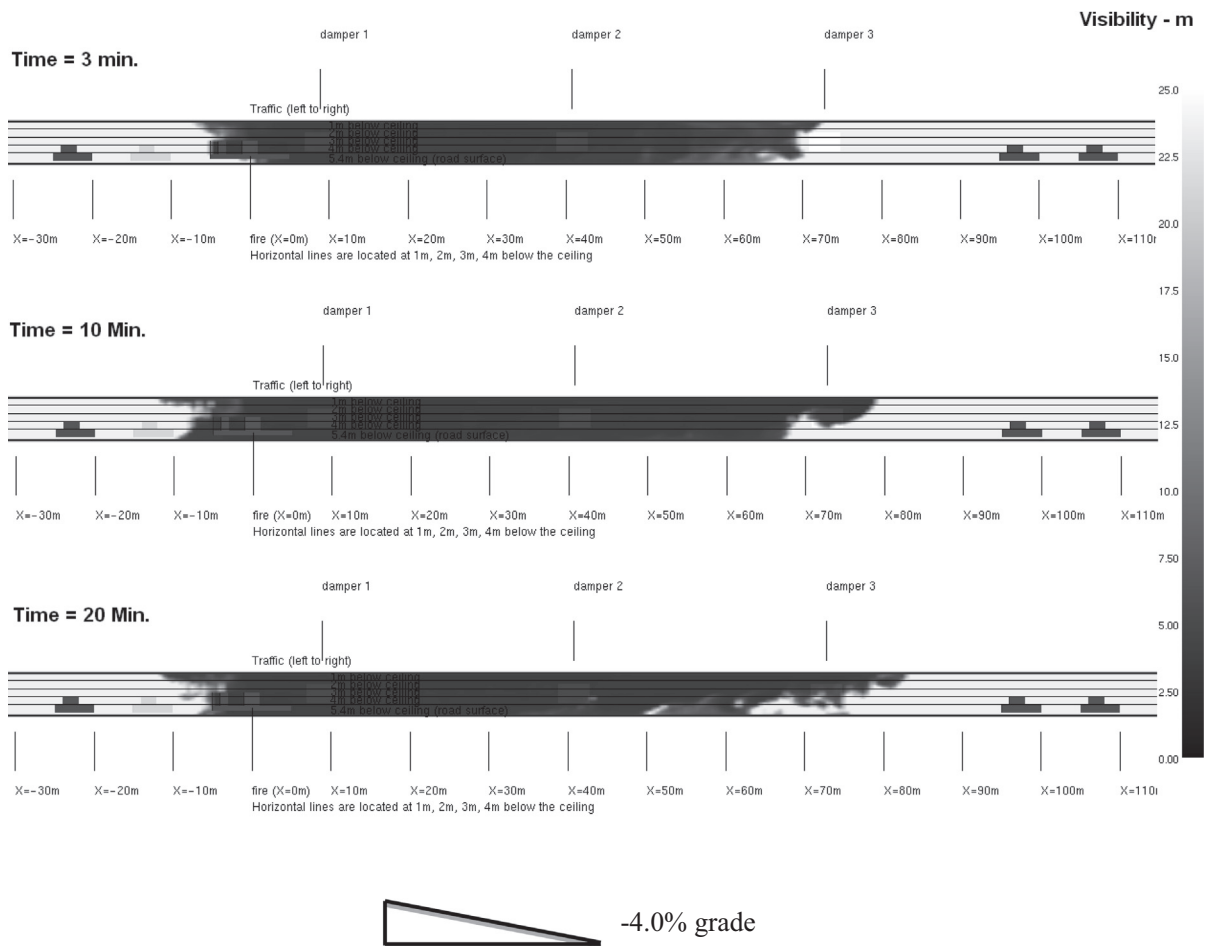


Fig. A5b. FDS predicted centerline visibility after 3, 10, and 20 min for Case E (CFD ID SR99NBjf-15a): Wall exhaust with 3 dampers, longitudinal ventilation  $u = 2.5$  m/s, gradient  $-4\%$ .

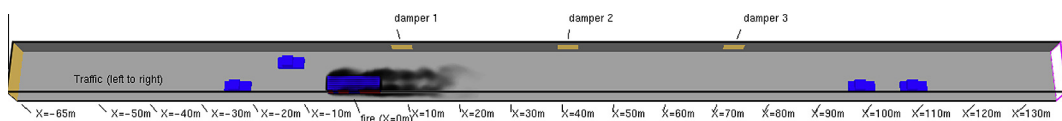


Fig. A6a. Plan view showing the fire location for Case F (CFD ID SR99NBjf-17a): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation  $u = 3.0$  m/s, gradient  $-4\%$ .

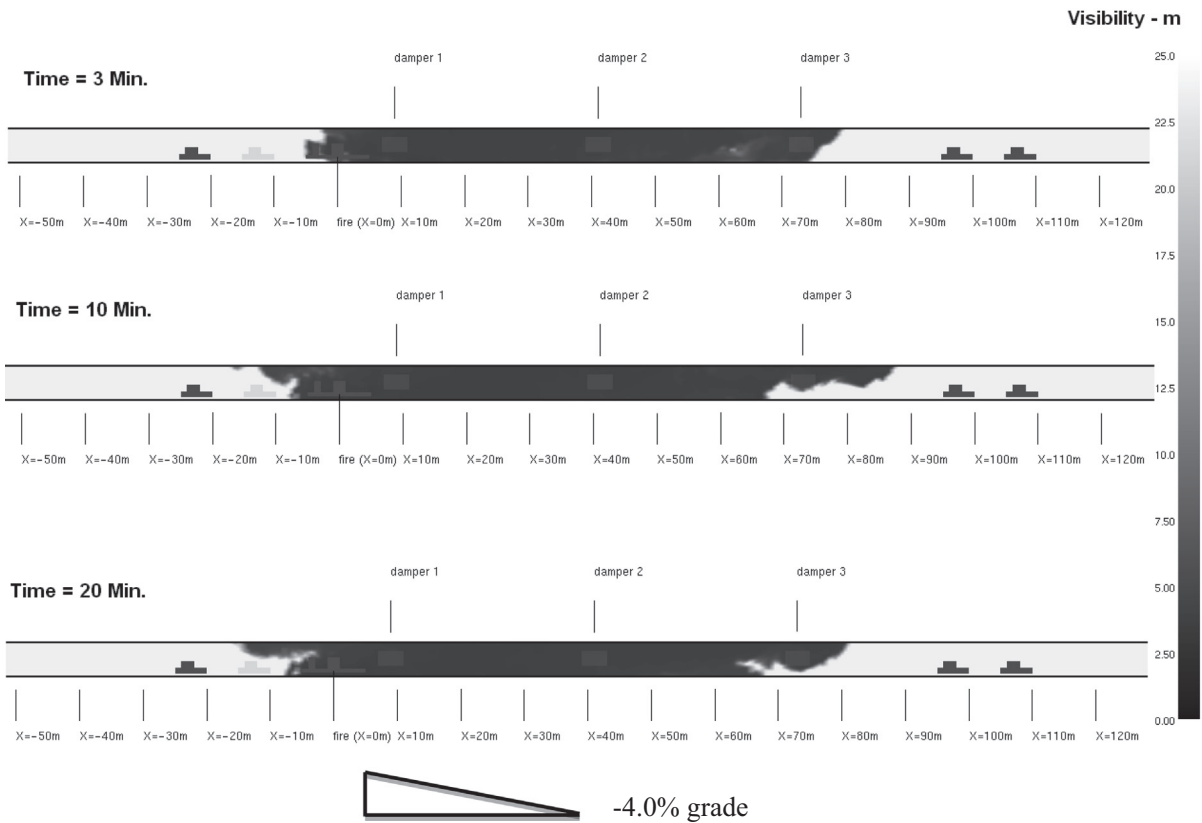
- There is no perceivable difference in the modified critical velocity for the case with and without upstream traffic blockages in the tunnel, at least for the cases with cars stopped upstream of a fire in this specific 2 lane tunnel.

In addition, it was also observed that extraction ventilation also limited the spread of the untenable condition zone within a local region of the tunnel. When considering the overall system performance, a modified critical velocity of 2–3 m/s, and operation of 3–5 dampers with a total face area of 30–50 m<sup>2</sup> was found to be able to control the smoke within a manageable fire zone.

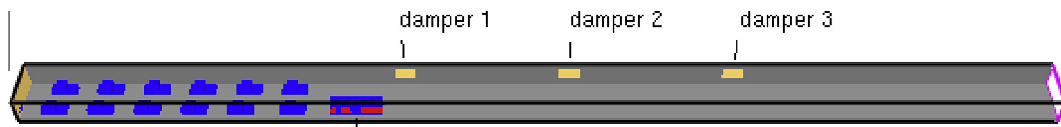
In conclusion, when the smoke extraction and fire suppression water spray cooling effects are considered, the standard critical velocity can be reduced by approximately 20–30%. As the smoke extraction rate is a function of outside air supply to the fire, this modified critical velocity will result in a reduction of the smoke extraction capacity and the associated vent duct plant size as well. A performance based analysis considering the specific tunnel ventilation and fire safety provisions is the key to optimizing the smoke control system.

**Appendix**

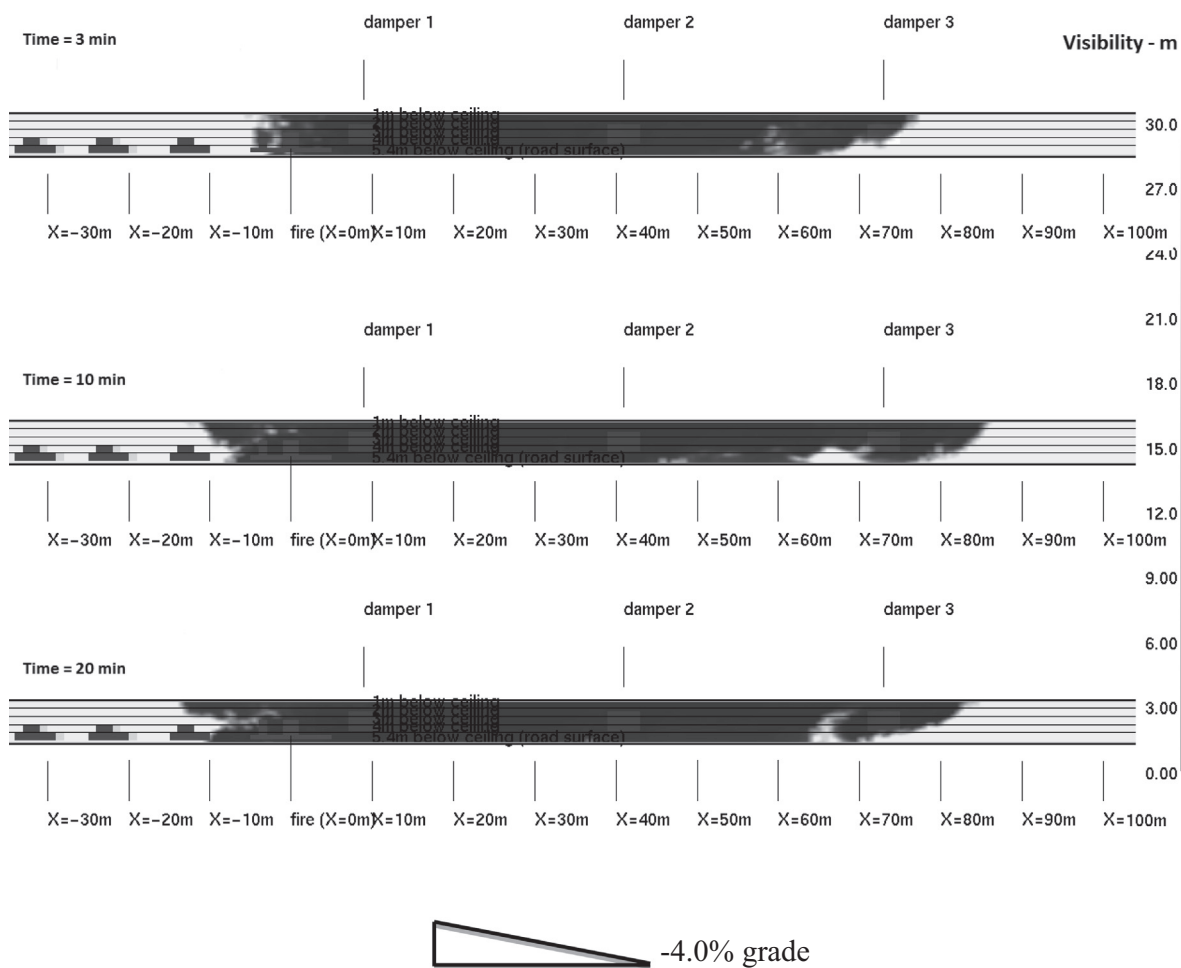
Visibilities simulated with CFD modeling are shown in Figures below:



**Fig. A6b.** FDS predicted centerline visibility after 3, 10, and 20 min for Case F (CFD ID SR99NBjF-17a): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation  $u = 3.0$  m/s, gradient  $-4\%$ .



**Fig. A7a.** Plan view shows the fire location for Case G (CFD ID SR99NBjF-20): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation  $u = 3.0$  m/s, gradient  $-4\%$ , upstream traffic jam.



**Fig. A7b.** FDS predicted centerline visibility after 3, 10, and 20 min for Case G (CFD ID SR99NBJF-20): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation  $u = 3.0$  m/s, gradient  $-4\%$ , upstream traffic jam.

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