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 when a traffic jam is built up caused by the fire incident.

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

In recent years, smoke extraction with a dedicated smoke duct along the entire length of the tunnel is gaining popularity because of its efficiency in extracting smoke and other fire generated hazards. In this paper, a modified critical velocity to control smoke back-layering while smoke extraction and fire suppression system are operating has been analyzed. This modified critical velocity is at least 20% lower than the critical velocity that is recommended in NFPA 502. This allows significant savings on ventilation capacity for the road tunnels which has a smoke extraction capacity with a dedicated smoke duct.

Based on a typical example road tunnel with a fixed extraction rate of 282m^3/s, Computational Fluid Dynamics (CFD) analysis has been performed to investigate the impact of the proposed smoke extraction system configurations, including extraction damper locations, number of operating dampers, tunnel gradient, fire location and impact of traffic jam upstream of the fire. It is concluded that the smoke extraction effects with the ceiling dampers or vertical wall-mounted dampers, fire location and the stopped vehicle blockages in the upstream doesn't make significant difference. However, tunnel gradient plays a major role on the modified critical velocity for a nominated design fire and smoke extraction rate.

Keywords: Tunnel fire, fire life safety, smoke management, critical velocity, modified critical velocity, tenability, smoke extraction, fire suppression, CFD

1. INTRODUCTION

Tunnel accident involving 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.

One of the design objectives of tunnel fire life safety system is to maintain a tenable condition for upstream regions of 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 tunnel untenable.

Several publications have discussed smoke control for occupants in the traffic upstream regions from the fire incident location[1-8]. However, the impact of smoke extraction on required critical velocity has not been investigated.

In newly built road tunnels, local extraction of smoke with a dedicated smoke exhaust duct is gaining popularity because of its effectiveness to mitigate fire hazards developing in the tunnel. For example, the renovated Mont Blanc Tunnel between France and Italy, the Clem 7 road tunnel and the airport link tunnel in Brisbane Australia, and the Alaskan Way Viaduct replacement tunnel in Seattle have adopted the concept of 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 affect smoke control with longitudinal flows that establish critical velocity as recommended in NFPA502 [9] for vehicular tunnels. However, this flow capacity does not take into account of the local smoke extraction effects.

In some tunnels in US, Japan and Australia, the sprinkler system is being utilized to actively control the fire spread and protect the tunnel structure. Unlike the tunnels with longitudinal ventilation, when the smoke exhaust and water based sprinkler fire suppression system are operating, this required upstream velocity can be reduced when the smoke extraction is enhanced with optimized damper operation configuration to effectively limit the spread of smoke and untenable conditions within a local tunnel segment.

The topic of this paper is to discuss the modified critical velocity for road tunnels where a dedicated smoke extraction is provided. The extraction rate will be determined considering the normal traffic, congested traffic and fire emergency conditions. Scenarios that have been discussed in this paper should take into consideration of the most critical fire conditions that may be encountered. Two different tunnel gradients have 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 tunnel gradient, fire location, smoke extraction location and total number of the opened smoke extraction dampers are also analyzed to confirm the performance of this modified critical velocity.

2. DESIGN METHODOLOGY AND PARAMETERS

Primary issues for the tunnel ventilation design are the required longitudinal ventilation air flow to push the smoke downstream preventing smoke backlayering, and the required smoke exhaust capacity when dedicated smoke extraction duct is considered.

To mitigate fire hazards from 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[10], a longitudinal ventilation velocity along the road tunnel should be controlled at around 3.0m/s to avoid smoke backlayering under fire conditions. 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. However when reviewing fundamental energy and fluid processes, this critical velocity requirement can be reduced when considering buoyant energy generated by fire is being removed from the tunnel by extraction rate.

To analyze the modified critical velocity, a segment representing a typical tunnel with a dedicated smoke duct as detailed in Table-1 has been investigated. According to the overhead fixed fire-fighting systems (FFFS)[11] prevalent in tunnel facilities across the world for managing road tunnel fires, a water application rate of 12 mm/min has been considered for all scenarios discussed in this paper.

With a trial and error study based on an initial longitudinal airflow from each portal of the tunnel and tunnel air cooling by overhead FFFS water spray, a fixed smoke extraction rate of 282 m^3/s is established with Subway Environment Simulation (SES) modeling for this example tunnel. The tunnel configuration and design parameters relevant to ventilation are listed in Table-1. The example tunnel is assumed to have a gradient ranges from -4% to +1.6%, and the tunnel roof height is assumed 6.2m from the road with a cross section area of 62 m^2. Considering the recent findings from the tunnel fire research in SP[12], the design fire is assumed 100 MW.

Figure 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. Therefore, the upstream longitudinal ventilation velocity that is required to prevent smoke backlayering and push the smoke downstream (i.e. longitudinal ventilation establishing critical velocity [9]) will be less than that is required for the condition that doesn't 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, its dependency on the other parameters has been investigated with CFD modeling approach.

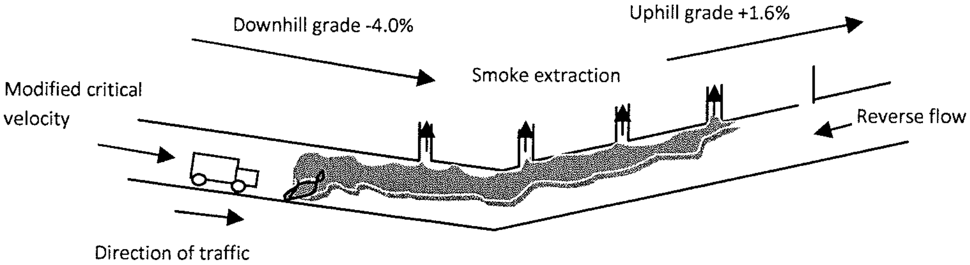

Figure 1: Schematic view of the tunnel fire smoke control system incorporating smoke extraction

Table-1: Parameters of tunnel configuration and ventilation system

Parameter	Value
Tunnel cross section area	$62m^2$
Tunnel ceiling height above road	6.2m
Design fire heat release rate (HRR)	100MW[12]
Sprinkler water application rate	12 mm/min
Smoke extraction rate	282 m^3/s (600,0000 cubic feet per minute at 20°C, computer model input 338.4kg/s)
Spacing of the dampers along the tunnel	33m (measured from center to center of the damper)
Effective opening area per damper	$10m^2$ for vertical dampers
Spacing of tunnel cross passage doors	198 m (measured from center to center)

Though this analysis is oriented toward 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. The fire heat release rate (HRR) grows from 0 to 86.8MW during the first 180 seconds, then grows at a rate of 0.92 MW/minute to 100MW. Ambient air temperature is assumed 20°C, and portal wind speed is assumed zero for all the cases.

The base case for this analysis considers a+1.6% gradient tunnel segment with longitudinal ventilation without smoke extraction. 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 that parameter. Variation sequences for the analyzed cases are as following:

A. Longitudinal ventilation, without smoke exhaust;
B. Based on case A, add ceiling exhaust with four pairs of remotely controlled addressable roof dampers spaced along the tunnel at 30 m in between (each location along the tunnel has two dampers, four pairs of operating dampers has eight dampers open, each damper has an opening area of $6.4m^2$), other parameters remain unchanged;
C. Based on case B, replace the ceiling dampers with side wall exhaust using four remotely controlled addressable vertical dampers, other parameters remain unchanged;
D. Based on case C, modify side wall exhaust with three remotely controlled addressable vertical dampers, other parameters remain unchanged;
E. Based on case D, modify the gradient from +1.6% uphill to -4.0% downhill, other parameters remain unchanged;
F. Based on case E, modify the fire location from the tunnel center to the far side from the wall dampers, other parameters remain unchanged;
G. Based on case F, include stopped vehicles for the upstream of the fire location, other parameters remain unchanged.

Computational Fluid Dynamics (CFD) modeling approach is employed to simulate and visualize the smoke flow behavior for the cases discussed above, so that the modified critical velocity can be determined to prevent smoke backalyering 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 of 10 m at 2.5m above the road has been used as the primary criteria for tenability and representative maker for other tenability parameters.

3. CFD MODELING AND ANALYSIS

Fire Dynamics Simulator (FDS)[13] version 5 developed by the National Institute of Standard and Technology (NIST) has been 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 20 years, this package has been validated extensively and being widely used in fire engineering community.

The computational domain includes a typical tunnel segment with a dimension of 200 m long, 10 m wide and 5.4 m high, the corresponding number of mesh cells is 400 x 25 x 27 for CFD modeling. Mesh size is 0.5m, 0.4m and 0.2m 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[13], the tunnel gradient is implement through the gravity vector. Open boundary conditions are assumed for the two ends of the tunnel segment that is modeled in this paper.

Table-2 gives an overview of all the cases that have been analyzed. Except for case A, all the cases listed in Table-2 considered an extraction rate of 338.4kg/s which is equivalent to an extraction rate of 282 m^3/s, when assuming an air density of 1.2kg/m^3 at ambient condition. This total effective extraction rate achieved at the fire location is calculated based on the critical velocity and the downstream make-up air flow, and is achieved with all the dampers on the wall or ceiling local to the fire open. The sprinklers are distributed on the ceiling of the tunnel with a spacing of 3m x 4m. For a water application of 12mm/min, each head with a total system discharge flow rate of 144 Liter of water per minute.

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. Actual duct flow conditions will not provide uniform extraction rate for each operating dampers, however, the flow differences will have insignificant impact to tenable region adjacent to 100 m zone where dampers are active. Furthermore, it was found that model length of 200 m provides acceptable clearance from model flow boundaries and region where extraction dampers influence flow within the tunnel. It is the effective total extraction rate local to the fire that controls the smoke propagation. The following is a discussion of significant model set up features and smoke control performance observations for each case.

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

Case A is a reference base case to determine the standard critical velocity that is required to control the smoke backlayering for a tunnel with a grade of +1.6%. Modeling method is based on longitudinal ventilation system being located far enough from fire so that upstream cross section velocity field is uniform. Figure 2a is a plan view showing the location of the fire. Figure 2b is an elevation view of smoke visibility of the tunnel centerline, showing an upstream longitudinal ventilation velocity of 3.0 m/s is required 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 is a variation from Case A. The only change is the roof extraction of 338.4 kg/s is implemented with four pairs of roof dampers spaced at 30m along the tunnel. Figure 3a shows the location of the roof dampers, which will open to extract the smoke from the vehicular tunnel. Figure 3b is an elevation view showing the CFD modeling visibility, which confirms that the smoke flows become stabilized after 3 minutes 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.

Case C - Wall damper extraction with4 wall dampers open, centered fire, grade +1.6%

Case C is a variation from Case B. The only change is the damper location. Wall dampers are spaced at 33m on the one side wall instead of roof dampers in Case B. The other wall has no smoke extraction dampers. Figure 4a and 4b show the fire location and the damper arrangement respectively. Fire is located at the tunnel roadway center. Figure 4c shows the modeled smoke visibility, which confirms that the modified critical velocity is 2.0m/s. This shows that the performance of the wall dampers is similar to that of the roof dampers, the modified critical velocity can be reduced to 2m/s when compared to the standard critical velocity of 3m/s.

Case D - Wall damper extraction with3 dampers open, centered fire, grade +1.6%

Case D is different from Case C because the opened dampers have been reduced from 4 to 3, assuming one damper fails. Figure 5a shows the location of the opened dampers. Figure 5b shows that CFD modeled visibility and confirms that modified critical velocity is 2.0m/s. Even with only 3 dampers operating, the smoke can still be controlled within approximately 100m.

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

Case E is different from case D because the grade is changed from +1.6% uphill to -4% downhill. Figure 6a shows the damper and fire location. Figure 6b shows the smoke visibility, and it confirms that the modified critical velocity of 2.5 m/s is required to control backlayering in a tunnel segment with a downhill gradient. The modified critical velocity is increased from 2.0 m/s to 2.5 m/s because the fire location is changed from an uphill -1.6% segment to a downhill -4% tunnel segment, therefore additional momentum from ventilation flow is 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 is a variation of Case E with a fire located on the far side of the wall with dampers, and the fire is located at the downhill -4% tunnel segment. Figure 7a shows the location of the fire and the dampers. Figure 7b shows the visibility field caused by the smoke flow and confirmed that the fire location doesn't significantly influence the smoke management. Supplemented with the smoke extraction, a modified critical velocity of 3.0m/s can control the smoke backlayering, which is a small increase compared to the case with the fire centered in the tunnel roadway.

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 is a variation of Case F, the difference when compared to Case F is that the upstream traffic blockage effects are included. Figure 8a show the location of fire, opened damper and the upstream traffic jam. Figure 8b 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. The stopped traffic blockage in the upstream doesn't make a perceivable different on the modified critical velocity for this specific scenario.

Table-2: Case analyzed with CFD considering an extraction rate $282\ m^3/s \times 1.2 kg/s = 338.4 kg/s$

Case ID	Exhaust location	Extraction dampers	Fire location	Gradient	modified critical velocity	Figures
Case A: SR99NBJF-19a	NA	None	Center	+1.6%	u=3.0 m/s	Figure 2a, 2b
Case B: SR99NBJF-13a	roof exhaust	4 pairs of dampers	Center	+1.6%	u=2.0 m/s	Figure 3a, 3b
Case C: SR99NBJF-14	wall exhaust	4 dampers	Center	+1.6%	u =2.0 m/s	Figure 4a, 4b and 4c
Case D: SR99NBJF-18a	wall exhaust	3 dampers	Center	+1.6%	u =2.0 m/s	Figure 5a, 5b
Case E: SR99NBJF-15a	wall exhaust	3 dampers	Center	-4.0%	u = 2.5 m/s	Figure 6a, 6b
Case F: SR99NBJF-17a	wall exhaust	3 dampers	Far side from wall exhaust	-4.0%	u = 3.0 m/s	Figure 7a, 7b
Case G: SR99NBJF-20	wall exhaust	3 dampers	Far side from wall exhaust	-4.0%	u = 3.0 m/s	Figure 8a, 8b
Note: "modified critical velocity" refers to the minimum required longitudinal velocity that ensures no back-layering in the upstream of the fire, considering the smoke extraction and sprinkler cooling effects.						

Visibilities simulated with CFM modeling are shown in the figures below.

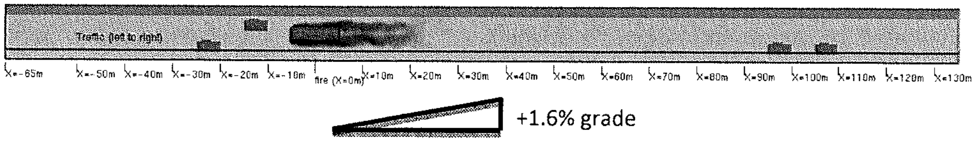

Figure 2a: Plan view of the fire location for Case A (CFD ID SR99NBJF-19a): No Exhaust, longitudinal ventilation u=3.0 m/s, grade +1.6%

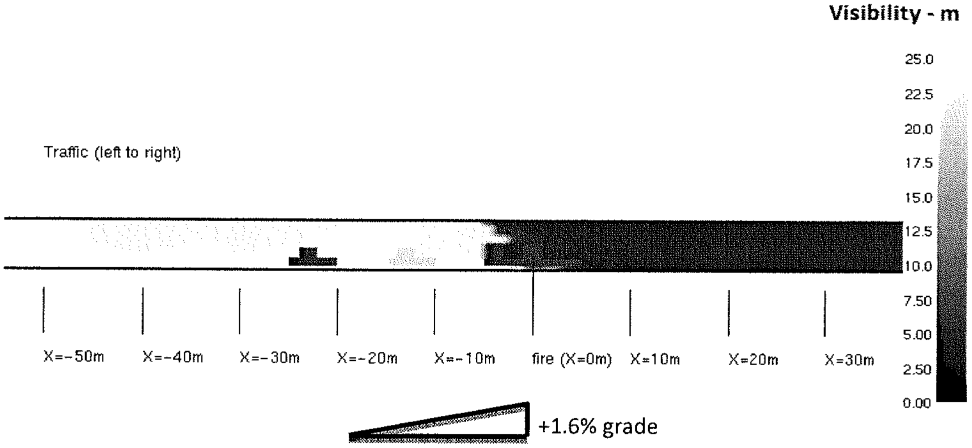

Figure 2b: Case A (CFD ID SR99NBJF-19a): No Exhaust, longitudinal ventilation u=3.0 m/s, no backlayering, grade +1.6%

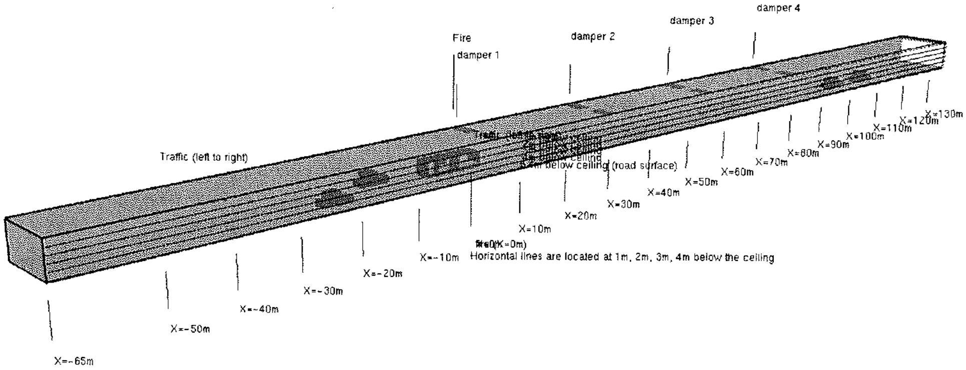

Figure 3a: A view showing the ceiling dampers for Case B (CFD ID SR99NBJF-13a): Ceiling exhaust, longitudinal ventilation u=2.0m/s, grade +1.6%

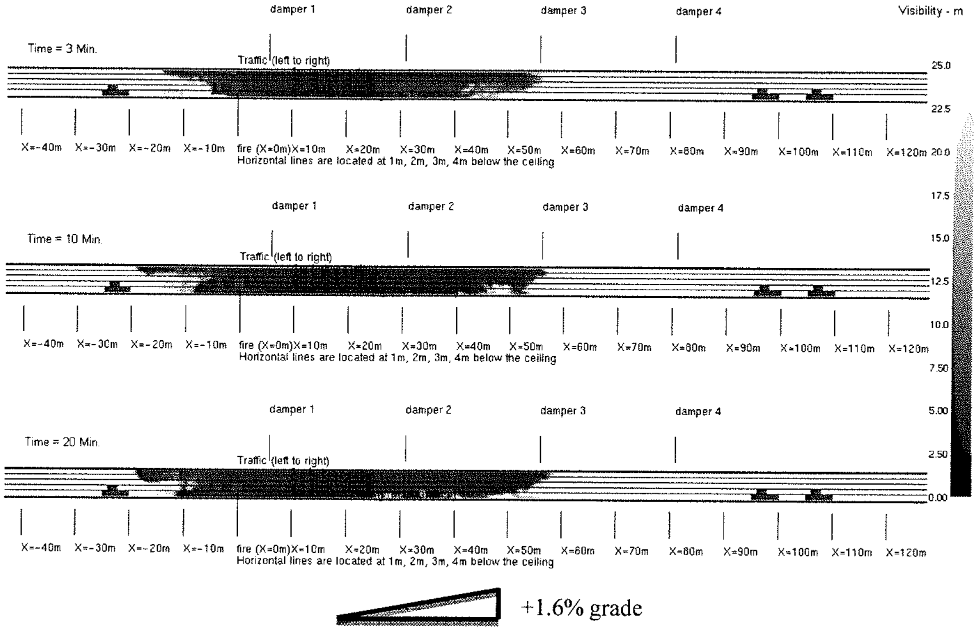

Figure 3b: FDS Predicted Centerline Visibility after 3, 10, and 20 Minutes for ceiling exhaust Case B (Case ID SR99NBJF-13a): Ceiling exhaust, longitudinal ventilation u=2.0m/s, grade +1.6%

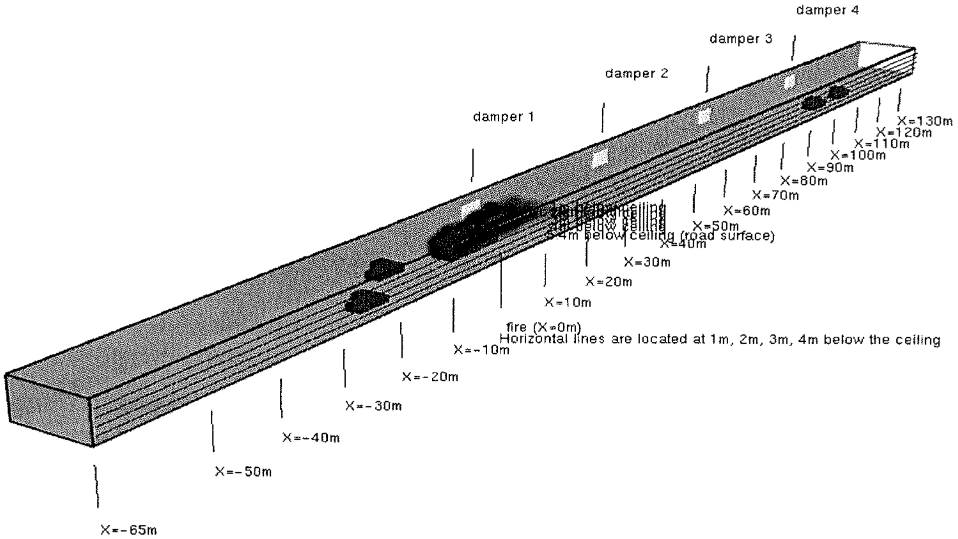

Figure 4a: A view showing the wall dampers for Case C (CFD ID SR99NBJF-14): Smoke exhaust with 4 wall dampers, longitudinal ventilation u=2.0m/s, grade +1.6%

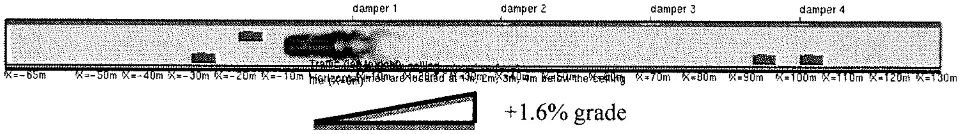

Figure 4b: A plan view showing the fire location for Case C (CFD ID SR99NBJF-14): Location of 4 wall exhaust dampers and fire location, longitudinal ventilation u=2.0m/s, grade +1.6%

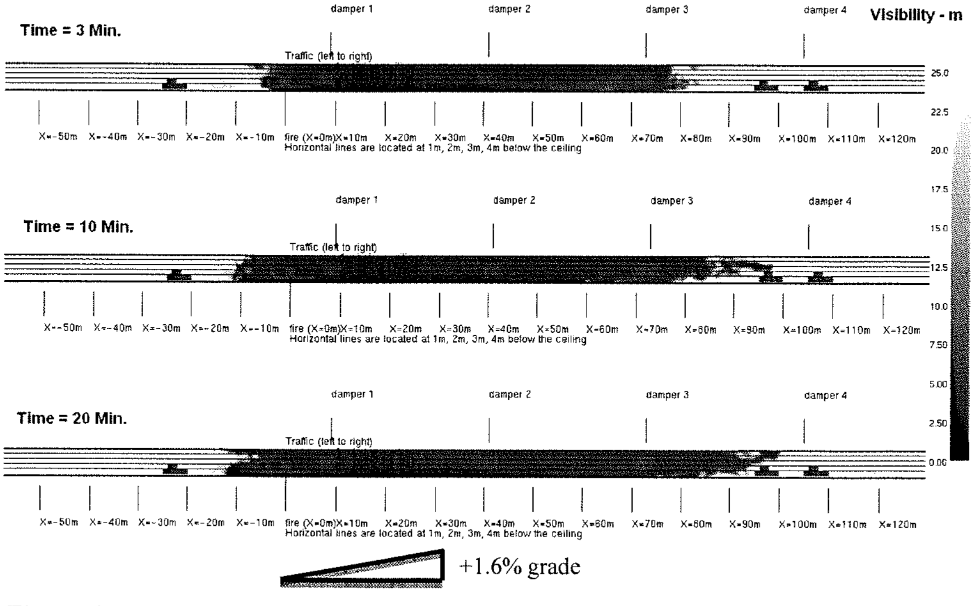

Figure 4c: CFD Predicted Centerline Visibility after 3, 10, and 20 Minutes for Case C (CFD ID SR99NBJF-14): Smoke exhaust with 4 wall dampers, longitudinal ventilation u=2.0m/s, grade +1.6%

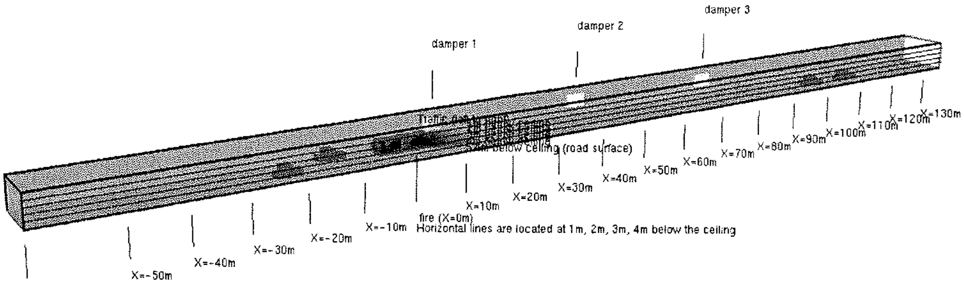

Figure 5a: Case D (CFD ID SR99NBJF-18a): Wall exhaust with 3 dampers, longitudinal ventilation u=2.0m/s

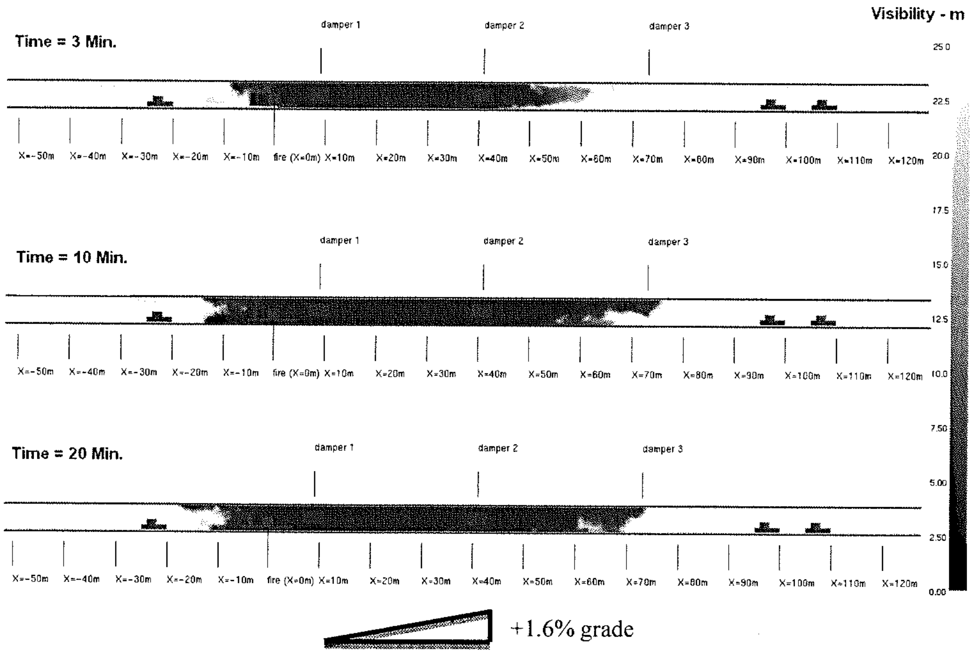

Figure 5b: FDS Predicted Centerline Visibility after 3, 10, and 20 Minutes for Case D (CFD ID SR99NBJF-18a): Wall exhaust with 3 dampers, longitudinal ventilation u=2.0m/s

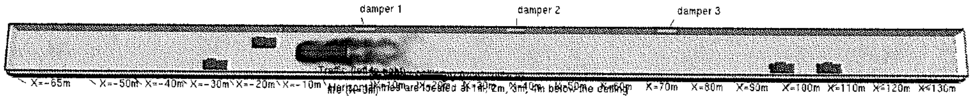

Figure 6a: Case E (CFD ID Case SR99NBJF-15a): Wall exhaust with 3 dampers, longitudinal ventilation u=2.5m/s, gradient -4%

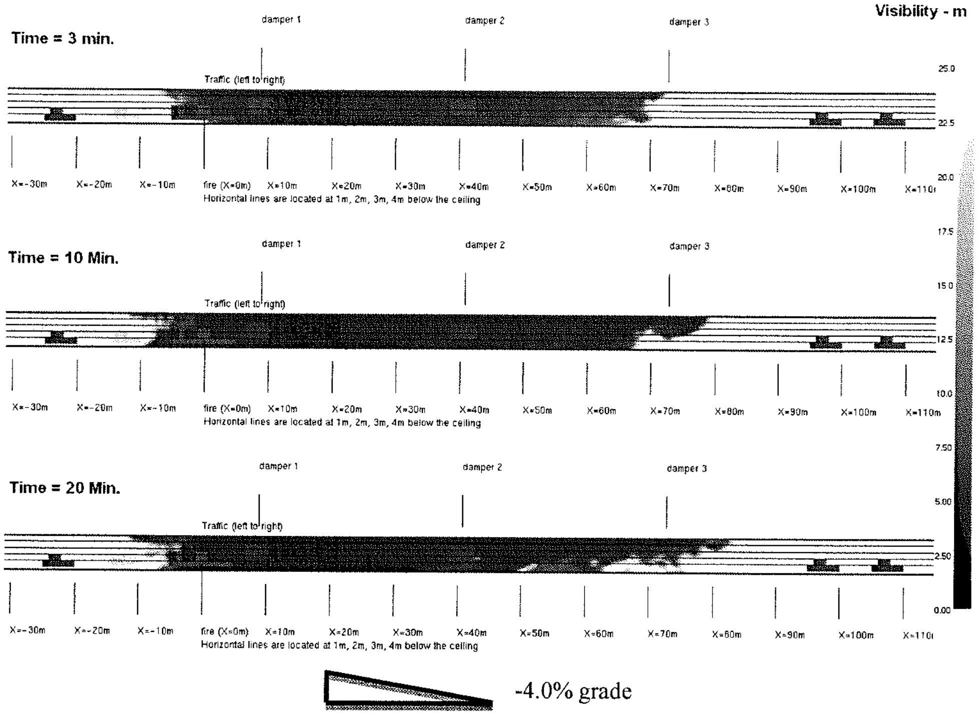

Figure 6b: FDS Predicted Centerline Visibility after 3, 10, and 20 Minutes for Case E (CFD ID SR99NBJF-15a): Wall exhaust with 3 dampers, longitudinal ventilation u=2.5m/s, gradient -4%

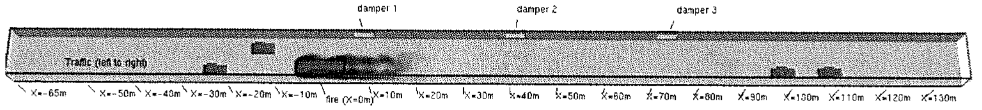

Figure 7a: Plan view showing the fire location for Case F (CFD ID SR99NBJF-17a): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation u=3.0m/s, gradient -4%

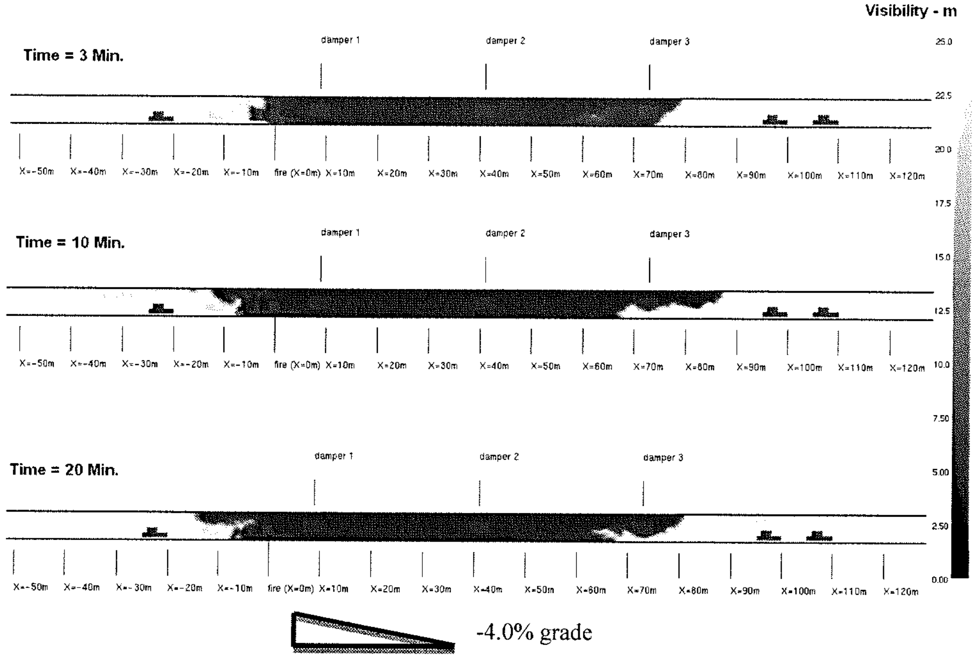

Figure 7b: FDS Predicted Centerline Visibility after 3, 10, and 20 Minutes for Case F (CFD ID SR99NBJF-17a): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation u=3.0m/s, gradient -4%

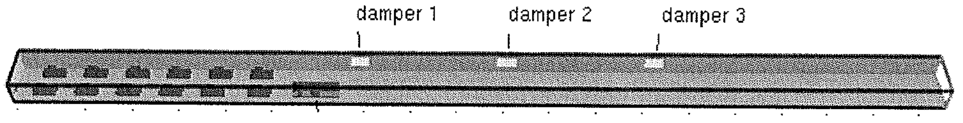

Figure 8a: Plan view shows the fire location for Case G (CFD ID SR99NBJF-20): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation u=3.0m/s, gradient -4%, upstream traffic jam

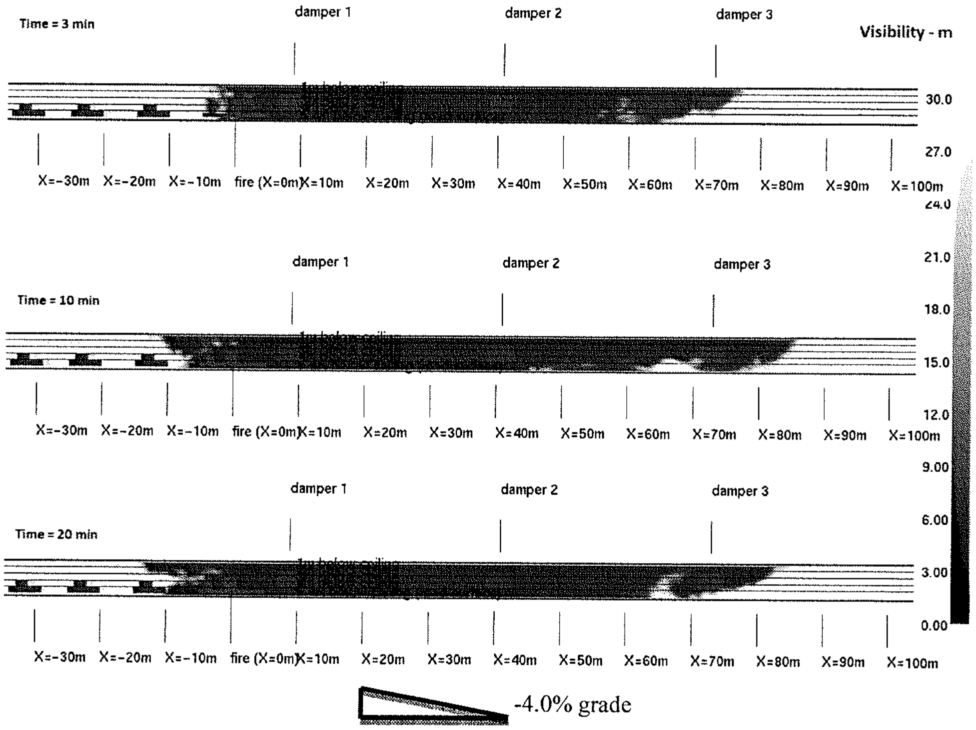

Figure 8b: FDS Predicted Centerline Visibility after 3, 10, and 20 Minutes for Case G (CFD ID SR99NBJF-20): Wall exhaust with 3 dampers, fire at far side from dampers, longitudinal ventilation u=3.0m/s, gradient -4%, upstream traffic jam

4. CONCLUSIONS

Computational Fluid Dynamics modeling 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 3m/s to 2m/s.
- It has been confirmed that the configuration with vertical side wall dampers and a configuration with horizontal roof mounted dampers develop equal capabilities to control smoke backlayering and prevent smoke propagation downstream of the tunnel; the required critical velocity is the same for both configurations.

- Tunnel gradient plays an important role in establishing the modified critical velocity for a given design fire scenario. Tunnel segment with -4% gradient demands a critical velocity of 2.5m/s, compared to 2.0m/s for a tunnel gradient of +1.6%.
- There is no significant impact on the critical velocity created by the number of operating dampers, 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 slightly higher critical velocity. A critical velocity of 3.0m/s would be required for a fire located near the wall. This is a slight increase compared to 2.5m/s for the case with fire located in the tunnel center.
- There is no perceivable difference in the demanded critical velocity for the case with and without upstream traffic blockages in the tunnel for the critical velocity discussed.

In addition, it was also observed that extraction ventilation also limited the spread of untenable zone within a limited region of the tunnel. For the vertical wall dampers spaced at 33m along the tunnel, the spread of smoke and untenable zone was limited to only a distance of approximately 100m. 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 to 50 m^2 was found to best control the smoke and untenable 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%, and this modified critical velocity will result in a reduction of smoke extraction capacity by 20 -30%.

5. REFERENCES

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