PROCEEDINGS, Fire and Evacuation Modeling Technical Conference (FEMTC) 2018
Gaithersburg, Maryland, October 1-3, 2018

NATURAL VENTILATION OF A SHORT ROAD TUNNEL

APPLICATION OF FDS+EVAC

Katie McQuade-Jones and Matt Bilson

WSP USA
One Penn Plaza
New York, New York, 10119
katie.mcquade-jones@wsp.com

ABSTRACT

For a road tunnel with a length around 305 m long or shorter, there is a question as to whether mechanical ventilation is necessary. To use natural ventilation, an engineering analysis must be conducted that demonstrates equivalency of life safety outcomes with mechanical ventilation. FDS+EVAC is used to quantify this equivalency of life safety outcomes for a short tunnel. The analysis accounts for toxic and irritant gas species impacts on evacuating occupants, as well as thermal impacts. The outcome is an FDS+EVAC analysis using FED and FIC, which provides a quantitative basis for the eventual code compliant (NFPA 502) solution.

INTRODUCTION

Short road tunnels, on the order of 120 to 300 m (400 to 1000 ft.) long, are becoming more common, driven by an increase in highway overbuilds. In the 1950s and 1960s, many highways in the United States were built through neighborhoods; as those highways are upgraded and rehabilitated, there is a trend toward lowering the roadway and reconnecting the divided neighborhoods with parks constructed over the new highway. To accommodate larger predicted traffic volumes, highways can also be widened, yielding a tunnel that is potentially four to six lanes wide (see Figure 1).

National Fire Protection Association (NFPA) Standard for Road Tunnels, Bridges and Other Limited Access Highways (NFPA 502) is applicable to the tunnel created by the overbuild. NFPA 502 does not mandate that mechanical ventilation be provided in tunnels less than 1000 m (3280 ft.) long, but does require an engineering analysis be performed. Historically, for short tunnels, common practice is that they are not mechanically ventilated. However, societal awareness about the serious nature of fires in road tunnels, coupled with the development of NFPA 502, has led to a need to demonstrate quantitatively whether mechanical ventilation is needed. NFPA 502 states that *emergency ventilation shall not be required in tunnels less than 3280 feet in length, where it can be shown by an engineering analysis that the level of safety provided by a mechanical ventilation system is equaled or exceeded by enhancing the means of egress or the use of natural ventilation*.

Traditionally, such analyses would use visibility as an acceptance criterion (typically > 10 m), however, this can be over conservative and lead to situations where all tunnels would require mechanical ventilation. This is inconsistent with many short tunnels in existence that are not ventilated. Instead, fractional effective dosage (FED) and fractional irritant concentration (FIC) are used to demonstrate a tenable egress environment in natural ventilation scenarios. FDS+EVAC is used to perform this analysis, which accounts for toxic and irritant gas species impacts on evacuating occupants, as well as thermal impacts. The results provide a quantitative basis for demonstrating equivalency of life safety outcomes between mechanical and natural ventilation. Per NFPA 502, final approval rests with the authority having jurisdiction (AHJ). The application of FDS+EVAC to the engineering analysis forms a crucial part of informing the AHJ as part of the approval process.

Figure 1: Highway traffic under a deck park / overbuild

DESIGN STANDARDS

The governing standard for roadway tunnels in the United States is NFPA 502; for this case study, the applicable edition was 2017. The overbuild tunnel in this study was 180 m (600 f.) long, classifying it as a category A tunnel per NFPA 502 Section 7.2.2. Section 11.1.1 of NFPA 502 states the following:

> *Emergency ventilation shall not be required in tunnels less than 1000 m (3280 ft.) in length, where it can be shown by an engineering analysis, using the design parameters for a particular tunnel (length, cross-section, grade, prevailing wind, traffic direction, types of cargoes, design, fire size, etc.), that the level of safety provided by a mechanical ventilation system can be equaled or exceeded by enhancing the means of egress, the use of natural ventilation, or the use of smoke storage, and shall be permitted only where approved by the authority having jurisdiction.*

To determine how to quantify the level of safety provided, further NFPA 502 sections are referenced. Section 11.2.2 states that the goal of a mechanical ventilation system "shall be to provide an evacuation path for motorists who are exiting from the tunnel and to facilitate fire-fighting operations." Provision of tenable conditions for egress is one way to meet this goal. This might be achieved, for example, by a longitudinal ventilation system sized to control the smoke for a certain design fire, but an equal egress outcome might be achieved by a system which doesn't have the same capacity. For example, a tunnel with exit doors spaced very closely may achieve the same outcomes for egress as a smoke control system.

To meet the NFPA 502 analysis requirement, a set of quantitative design criteria were developed to show equivalence between mechanical and natural ventilation schemes, by analyzing the tenability of the egress path. The criteria used include the fractional effective dose (FED) of toxic gases and heat experienced by egressing occupants, as well as the fractional irritant concentration (FIC).

APPLICATIONS

There are many examples setting precedent for naturally ventilating short tunnels. A survey of (randomly selected) short tunnels and their ventilation schemes is given in Table 1. It is worth noting that some of the tunnels listed are mechanically ventilated, indicating that a natural ventilation scheme may not be appropriate in all short tunnels.

Table 1: Ventilation schemes of various Category A and B tunnels

Name	Length m (ft.)	Urban/ rural	Traffic	Year	Ventilation
St Louis, Park of I44, Missouri	70 (230)	U	Bi	2014	Natural
Banora Underpass, Australia	77 (253)	U	Bi	2012	Natural
5 Freeway, Elysian Valley, California	91 (300)	U	Uni		Natural
M1 Motorway, Coomera, Australia	100 (328)	U	Bi	1998	Natural
IH3, HI	107 (350)	R	Uni		Natural
I95 Park, Penns Landing, Pennsylvania	116 (380)	U	Uni		Natural
I5 Tunnel, Seattle, WA	167 (547)	U	Uni	1988	Natural
Newhall Pass, California	167 (550)	U	Uni	1971	Natural
Dyer Avenue, New York	168 (550)	U	Bi	*	Mechanical
Pasadena, I210, California	169 (556)	U	Uni	2003	Natural
Garden State Parkway, New Jersey	174 (571)	U	Bi		Natural
Peachtree Rd, Buckhead, Georgia	176 (578)	U	Uni		Mechanical
Rockville, Intercounty Conn, Maryland	195 (640)	R	Bi	2010	Natural
Oak Park, Detroit, Michigan	213 (700)	U	Uni		Natural
AMETI, Auckland, New Zealand	225 (738)	U	Bi	2010	Natural
Pasadena, I210, California	248 (815)	U	Uni	2003	Natural
Idaho Springs, Colorado	250 (820)	R	Uni	2015	Natural
I84 - Trumbull St, Connecticut	262 (860)	U	Bi		Natural
Pasadena, I210, California	271 (889)	U	Uni	2003	Natural
Washington Avenue, Holland, MI	274 (900)	U	Uni		Mechanical
College Avenue Tunnel, Milwaukee, WI	277 (910)	U	Uni	2010	Mechanical

* Under construction

METHOD

The goal of this work was to provide a code compliant design that would ultimately be sufficient for approval consideration by the AHJ. It was necessary to show via engineering analysis, in accordance with NFPA 502, that "the level of safety provided by a mechanical ventilation system can be equaled or exceeded by… the use of natural ventilation." This requirement is effectively allowing a performance-based approach to fire-life safety for a short road tunnel. A quantitative approach to demonstrating equivalent performance (using FDS+EVAC) was adopted because it allows the most transparent and thorough comparison between options, as opposed to a qualitative approach.

The first step in the approach was to develop a set of criteria quantifying safety. NFPA 502 Section 11.2.2 states that "in all cases, the desired goal shall be to provide a tenable evacuation path for motorists who are exiting from the tunnel." To this end, safety was defined as all occupants being able to self-evacuate, meaning none were incapacitated by smoke or heat. Quantifying this was done using the fractional effective dose (FED) of toxic gases and heat experienced by egressing occupants, as well as the fractional irritant concentration (FIC) experienced during evacuation. The following criteria checks were applied:

1. Were any occupants exposed to an FED of hazardous gases that resulted in incapacitation? An FED greater than 0.3 was taken as exceeding the minimum level for incapacitation. More specifically, an FED of 0.3 is the incapacitation threshold for the most sensitive 1% of people (Purser, SFPE).
2. Were any occupants exposed to an FED of heat that resulted in incapacitation? Per NFPA 502 Annex B.2.1, the incapacitation threshold value is 0.3.
3. Were any occupants exposed to an incapacitating FIC during their evacuation? The conservative value of 0.3 was also used here. (Purser, SFPE)

To calculate the FED and FIC, FDS+EVAC version 6.6 was used. EVAC directly tracks the toxic gas FED of each occupant. Because the agent-based evacuation process is stochastic, multiple iterations were run and averaged. For each case, 40 evacuation simulations were run. FIC was visually inspected using a contour slice file at 2.4 m above the roadway. Concentration limits for computing the FED and FIC for each species, and the subsequent aggregate effects on occupants were computed using Purser's model (Purser, SFPE), which is documented in the FDS User Guide (McGrattan et. al).

EVAC does not track the temperatures experienced by each occupant, so the tunnel temperature and visibility profiles were output and used to calculate the thermal FED separately. The temperature FED was calculated using the NFPA 502 Annex B formulas. An occupant's FED was calculated based on temperatures encountered as the occupant moved through the tunnel. Occupant speed was decreased if visibility decreased, based on the same equations implemented by EVAC. This then accounts for any additional exposure to high temperatures when moving through regions of low visibility. Partial FEDs were calculated every 5 seconds during the egress and were summed. The analysis was performed using the slowest default EVAC occupant, giving the maximum thermal FED.

Inputs

The boundary conditions for the FDS file were as follows:

- Exit portal (see Figure 2) is an open boundary at far field conditions.
- Entrance portal is specified as a velocity profile. The velocity was determined by 1D calculation, factoring in appropriate friction effects on air movement, and accounts for:
    - The piston effect from moving traffic at the start of the incident (moving at 70 km/hr).
    - The 95th percentile adverse wind (see Figure 2) of 5.5 m/s.
    - Frictional losses due to stopped traffic.
    - The ramp up time of jet fans (for the mechanical ventilation cases).
    - The friction factor of the tunnel surfaces.
    - The installation factor of the jet fans (0.8).
    - Fire pressure loss effects were assumed negligible on the velocity profile since the analysis was dealing with the early growth stages of the fire.

The fire location was near the exit portal, giving the longest possible egress distance (see Figure 2). Per NFPA 502 Annex B.3, a region of untenability of 30 m (100 ft.) around the fire was applied, due to the large design fire sizes tested. The egress route in most cases was upstream to the entrance portal. In some cases, egress doors were placed every 60 m to test their effect on the FED results. Cars were placed in the model as obstacles to occupants; the passenger car unit length, including space between vehicles was 6.7 m (PIARC, "Road Tunnels"). Using the number of vehicles stopped behind the fire vehicle, 1.5 occupants were added per vehicle. The default EVAC parameters were used for male, female, elderly, and child occupants. The population makeup was 40% male, 40% female, 10% elderly, and 10% children, which was consistent with typical urban census data.

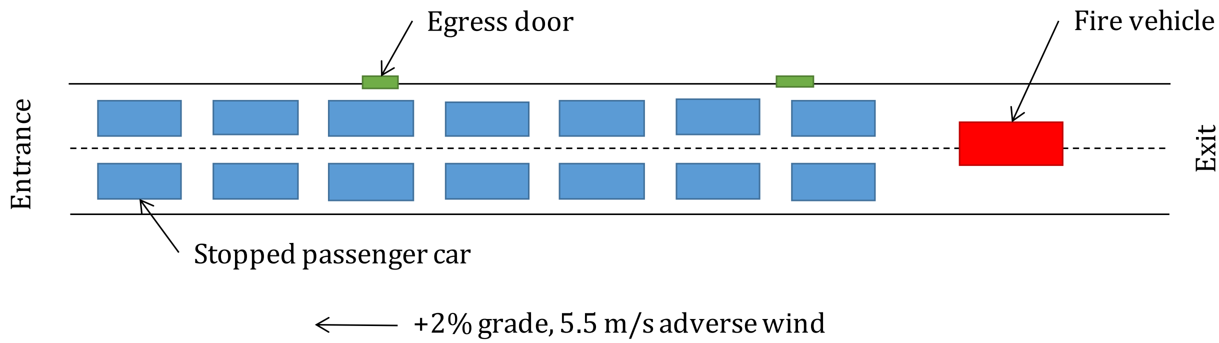

Figure 2: Schematic layout of two-lane tunnel and fire scenario

To accurately model FED/FIC, a full combustion reaction including irritants and asphyxiants was used. The proportions of irritants and asphyxiants were taken from experimental data of a full-scale automobile fire (Lonnermark). The combustion product yields are as per the full scale test and are listed in Table 2.

Table 2: Combustion product yields

Combustion product	Value (kg/kg fuel)
Soot	0.1954
CO	0.0630
HCl	0.0130
HCN	0.0016
SO_2	0.0050
C_3H_4O	0.0003
CH_2O	0.0011

To input these into FDS, a combustion reaction coefficients were solved for using a typical polymer, GM21, as the fuel. The heat of combustion was set as per the full scale test (35 MJ/kg). The soot yield was that of GM21 scaled to produce the same amount of soot with an adjusted heat of combustion of 35 MJ/kg (SFPE Handbook). This gives a conservative soot yield, as it represents a predominantly polymer-based vehicle. To balance the reaction, the fuel molecule input to FDS was $CH_{1.8}O_3N_2Cl_{0.017}S_{0.004}$.

The fire heat release rate (FHRR) curve was a linear growth rate of 1 MW/min for the first two minutes followed by 20 MW/min until it reached 300 MW, representing a dangerous goods vehicle (DGV) fire (e.g. a bulk fuel carrier). In addition to a DGV fire, a heavy goods vehicle (HGV) fire was tested (e.g. a semi-trailer truck). The HGV fire grew to 4 MW in the first 7 minutes, and then up to 140 MW at 15 MW/min after that (PIARC, “Design Fire”).

<u>Scenarios</u>

To investigate the comparison of natural to mechanical ventilation, various scenarios were tested which included combinations of the following inputs:

- Dangerous good vehicle (DGV) fires versus heavy goods vehicle (HGV) fires
- Quantity of egress doors along the tunnel
- Length of tunnel (180 m and 305 m)
- Quantity of lanes (2 lane tunnels were 10 m wide, 6 lane tunnels were 30 m wide)

For a more detailed listing of each case, refer to Table 3.

Table 3: FDS simulations list

Case number	Ventilation	Egress doors	FHRR	Tunnel length	Lanes
FEM-01-01	Natural	0	300 MW	180 m	2
FEM-01-02	Mechanical	0	300 MW	180 m	2
FEM-01-03	Natural	2	300 MW	180 m	2
FEM-01-04	Natural	0	140 MW	180 m	2
FEM-01-05	Mechanical	0	140 MW	180 m	2
FEM-01-06	Natural	2	140 MW	180 m	2
FEM-01-07	Natural	0	300 MW	180 m	6
FEM-01-08	Mechanical	0	300 MW	180 m	6
FEM-01-10	Natural	0	140 MW	305 m	2
FEM-01-11	Mechanical	0	140 MW	305 m	2
FEM-01-12	Natural	0	300 MW	305 m	6
FEM-01-13	Mechanical	0	300 MW	305 m	6

RESULTS

The maximum toxic gas FED, heat FED, and toxic gas FIC for each case are presented in Table 4. When calculating the heat FED in cases with egress doors, the occupant was assumed to use the first available egress door. Visibility contours at 2.4 m above the roadway were inspected to confirm the egress door remained visible (>10 m) at the time the occupant would reach the door. The maximum toxic gas FED was taken from the 40 EVAC simulations. The maximum toxic gas FIC was visually inspected from contours at 2.4 m above the roadway.

To be considered a passing result, all FED/FIC values must be below 0.3. Results were not compared on a numerical basis, instead a pass/fail criterion was used.

Table 4: FED/FIC results of FDS simulations

Case number	Avg. egress time (s)	Max. egress time (s)	Max. FED, toxic gases	Max. FED, heat	Max. FIC	Pass/fail
FEM-01-01	145	800	0.081	1.00	1.00	Fail
FEM-01-02	148	313	0.003	0.02	0.20	Pass
FEM-01-03	125	120	0.013	0.00	0.05	Pass
FEM-01-04	148	310	0.002	0.01	0.05	Pass
FEM-01-05	148	307	0.002	0.01	0.05	Pass
FEM-01-06	127	130	0.001	0.00	0.05	Pass
FEM-01-07	149	335	0.003	0.02	0.20	Pass
FEM-01-08	149	325	0.001	0.01	0.10	Pass
FEM-01-10	214	638	0.012	0.06	0.35	Fail
FEM-01-11	210	576	0.002	0.01	0.05	Pass
FEM-01-12	214	695	0.067	0.20	0.55	Fail
FEM-01-13	212	574	0.001	0.01	0.10	Pass

In summary, the results showed that for the 180 m tunnel length, portal egress only was equivalent to mechanical ventilation for some scenarios (see Table 5). At the 305 m length, neither of the natural ventilation scenarios met the FIC design criteria (FEM-01-10 and FEM-01-12). These cases did not include any egress doors, however, because the FIC was noted to increase above 0.3 after 400 s, there is likely a quantity and spacing of doors that would give a passing result.

Table 5: FED/FIC results of FDS simulations

Length (m)	Lanes	Design fire	Provisions to meet NPFA 502 with natural ventilation
180	2	HGV	Portal egress
180	2	DGV	Additional egress doors
180	6	DGV	Portal egress
305	2	HGV	Additional egress doors
305	6	DGV	Additional egress doors

Traditional methods for proving a tenable environment tend to focus on maintaining 10 m (30 ft.) of visibility along the egress path. However, recent work has suggested that occupants can move through visibilities of 2 m for 20-60 minutes before becoming incapacitated (Purser, "Toxic Effects"). For the shorter tunnels analyzed in this case study, egress times are on the order of 5-15 minutes. Figure 3 shows visibility 2.4 m above the roadway for case FEM-01-04 (HGV fire) at 90 s, when occupants closest to the fire begin to evacuate. The conditions in the tunnel are also shown in an isometric view in Figure 4, along with the EVAC occupants and outlines of vehicles. Figure 5 shows the same case at 150 s, when half of occupants have exited. Average visibility in the tunnel is around 7 m. Figure 6 shows visibility at 310 s, when the last person exits at the entrance portal. The average visibility along the egress path is 4 m, and the FED and FIC results are all below 0.3. The results indicate that a tenable egress environment is maintained, and this is supported by Purser's work.

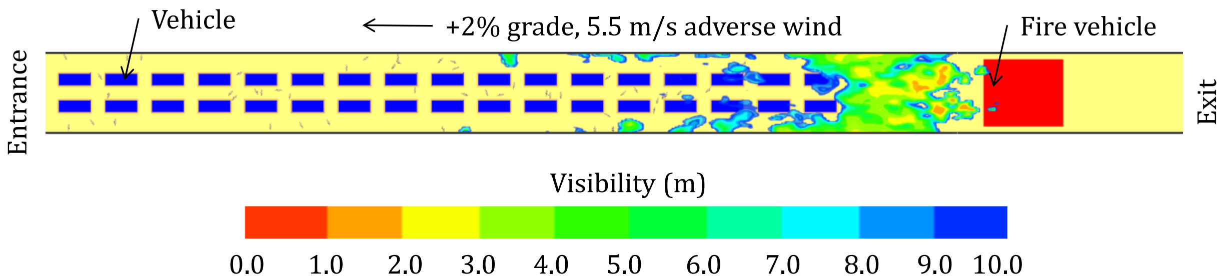

Figure 3: Case FEM-01-04, plan view of visibility at 2.4 m above roadway at 90 s (occupants closest to fire begin to move)

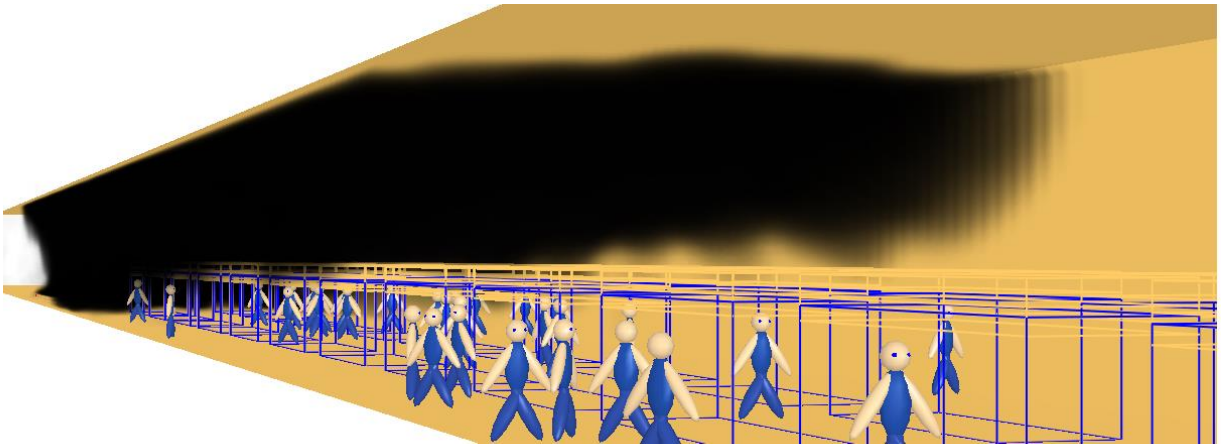

Figure 4: Case FEM-01-04, isometric view of smoke and EVAC occupants at 90 s, with vehicle outlines shown (occupants closest to fire begin to move)

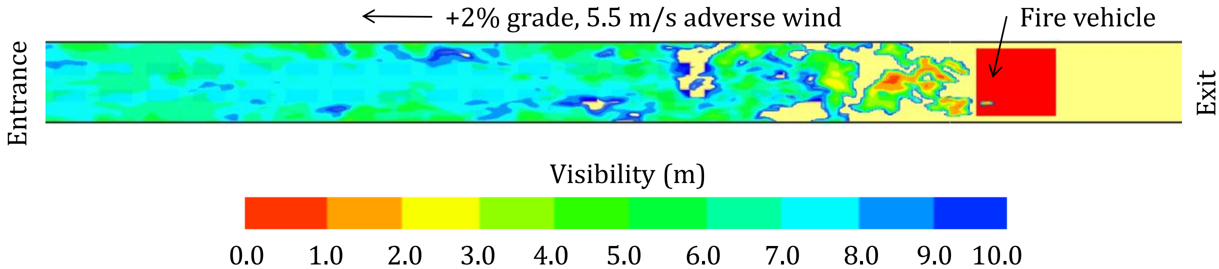

Figure 5: Case FEM-01-04, plan view of visibility at 2.4 m above roadway at 150 s (half of occupants exited)

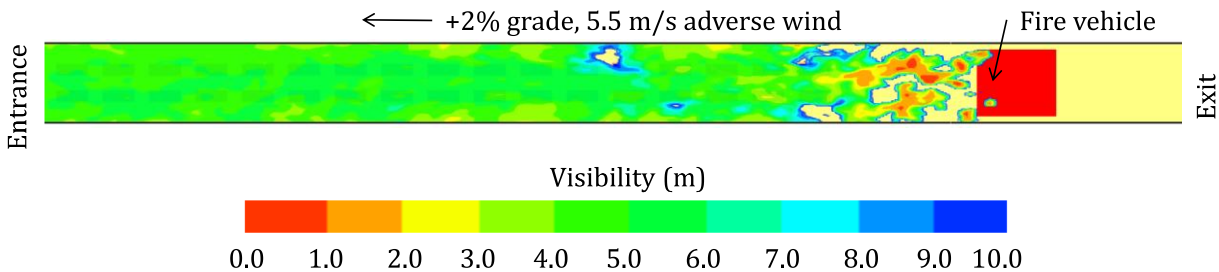

Figure 6: Case FEM-01-04, plan view of visibility at 2.4 m above roadway at 310 s (last occupant exits)

Although the visibility is reduced as occupants egress, the temperatures along the egress path are reasonable. Figure 7 shows an elevation view of temperature, with occupants experiencing between 24 and 28°C.

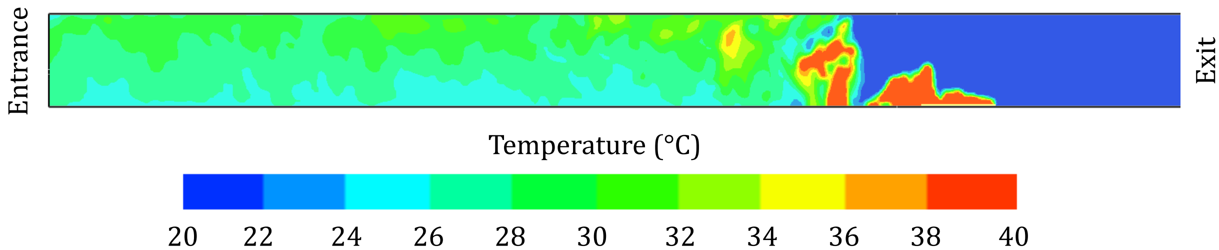

Figure 7: Case FEM-01-04, elevation view of temperature at 310 s (as last occupant exits)

Looking at one of the DGV fire natural ventilation cases, FEM-01-07, visibility along the egress path is primarily 2-4 m, with some pockets of no visibility (Figure 8). This case also had a passing result, and the visibility, though reduced, is in line with what was shown by Purser as tenable for some time.

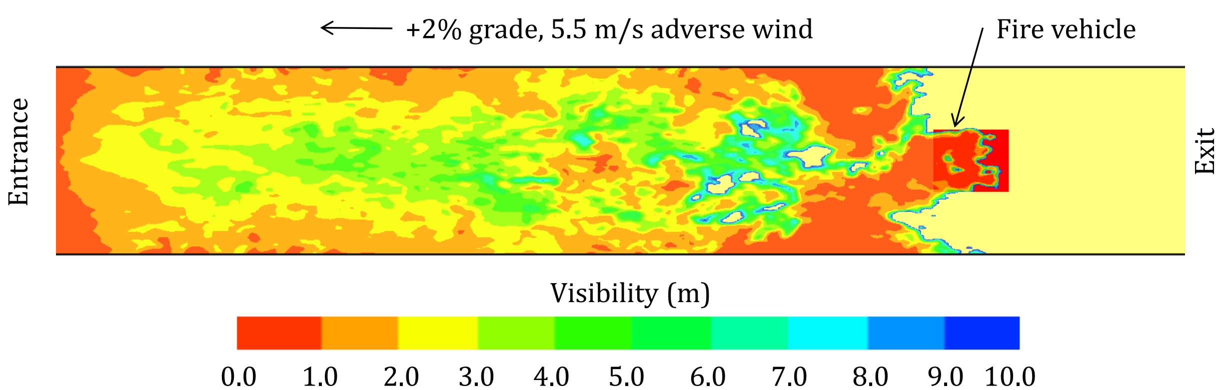

Figure 8: Case FEM-01-07, visibility at 2.4 m above roadway at 335 s (as last occupant exits)

SUMMARY

The application of FDS+EVAC, along with detailed accounting of combustion products, incorporating asphyxiant and irritant species derived from a full-scale car fire burn, has been applied to the case study of a short road tunnel with natural ventilation. The results of the analysis, interpreted based on FED and FIC impacts, have been used to provide a quantitative test of the fire-life safety performance outcomes for mechanical and natural tunnel ventilation schemes. The results have been used to make the case for equivalency of the ventilation influence on life safety outcomes for the two design options, in accordance with NFPA 502.

The significance of the use of FDS+EVAC here is that it enables consideration of performance using visibility, thermal, and FED/FIC considerations, instead of just visibility and heat alone. The analysis shows that interpretation on visibility alone would deem a result unacceptable. Consideration of FED and FIC allows for a conclusion that occupants can still evacuate safely, even if visibility is expected to be severely reduced.

Mechanical ventilation is frequently necessary in tunnels, but it adds components, complexity and cost. When the tunnel length is around 300 m long or shorter, there is always a question as to whether mechanical ventilation is necessary or not. Ideally, mechanical ventilation would not be provided for very short facilities. This paper has demonstrated a quantitative approach to answer the question, and form a basis for AHJ approval. Results from this case study showed that a 180 m long two-lane tunnel with a heavy goods vehicle design fire can be naturally ventilated, while a 305 m long tunnel requires mechanical ventilation or an additional safety feature, such as additional egress doors.

REFERENCES

Lonnermark, A. and Blomqvist, P. (2006), “Emissions from an Automobile Fire,” *Chemosphere*, **62**, 1043-1056.

McGrattan, K. et. al (2017), “Fire Dynamics Simulator User’s Guide.”

National Fire Protection Association (2017), “NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways,” 2017 Edition.

PIARC (2016), “Design fire characteristic for road tunnels.”

PIARC (1995), “Road Tunnels: Vehicle Emissions and Air Demand for Ventilation.”

Purser, D. (2018), “How to Determine Toxic Effects and Human Behaviour when Exposed to Fire Smoke in Underground Facilities – Challenges and Possibilities,” *International Symposium on Tunnel Safety and Security,* Boras, Sweden.

Purser, D. and McAllister, J. (2016), “Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat,” *SFPE Handbook of Fire Protection Engineering Fifth Ed.,* Vol. 3, 2308-2428.

SFPE Handbook of Fire Protection Engineering Fifth Ed., Appendix A, 3397-3492.