PROCEEDINGS, Fire and Evacuation Modeling Technical Conference (FEMTC) 2014
Gaithersburg, Maryland, September 8-10, 2014

EVACUATION MODELING IN ROAD TUNNEL FIRE EVENTS, CFD INFLUENCING EVACUATION RESULTS

Toby Sargant, Pedestrian Analyst, CEng
Sonja Nightingale, Senior Pedestrian Modeler, CEng
Oliver Dinsdale-Young, Mechanical Engineer, CEng
Jay Ganeshalingam, CFD Modeler, PhD

Hatch Mott MacDonald
1400 Broadway
New York, NY 10018
toby.sargant@hatchmott.com

ABSTRACT

The evacuation of pedestrians from a road tunnel in the event of a fire is linked to the tenability of the environment the pedestrians are walking through, with the following factors generally assessed:

- Visibility
- Local air temperature
- Radiant heat flux from the fire and hot smoke layer
- Carbon monoxide concentration

Based on project experience, presented here are the modeling technologies and techniques that have been employed in studying the evacuation of multilane road tunnels using Mott MacDonald's proprietary STEPS pedestrian modeling software, coupled with computational fluid dynamics (CFD) predictions.

The model presented contains CFD data input directly from the Fire Dynamics Simulator (FDS) software that predicts the four factors listed above within the tunnel during the evacuation. The walking speed distributions of the passengers are directly affected within the STEPS model by the visibility information from the CFD results. The cumulative carbon monoxide dose received by each pedestrian was calculated throughout the simulations, from which Fractional Effective Dose (FED) calculations were performed.

The vehicles within the tunnel include a mixture of different types, ranging from private cars to public vehicles such as buses. Pre-movement times used within the model were varied depending on proximity to the fire location along with the time taken to vacate coaches or buses. The influence of people of reduced mobility (PRM) was included in the model.

The results provide detailed information regarding overall evacuation times and the tenability of the environment for the evacuating pedestrians during their evacuation. Presented are the times taken to evacuate the different sections of the tunnel, which include the slowing effect, seen on walking speeds resulting from the inclusion of CFD results.

Additionally the FED results chart the tenability of the environment that the pedestrians experience along their evacuation routes. These results can only be obtained in such detail by combining CFD results with sophisticated pedestrian modeling software such as STEPS.

PURPOSE

The purpose of this paper is to explore the factors that can be considered when employing pedestrian modeling techniques to analyze the evacuation time and tenability conditions during a fire incident using typical section of a bidirectional road tunnel as an example.

The paper focuses on the pedestrian modeling component of the calculations with the CFD modeling performed in the FDS Version 6.0.1 software being used as an input without detailed discussion as to its generation.

METHODOLOGY

The first stage of the analysis was to undertake CFD modeling in FDS, providing predictions of the extinction coefficient, temperature, radiant heat flux and carbon monoxide concentrations on a slice plane located 2.5 meters above the road level, as per the National Fire Protection Association (NFPA) 502 standard.

The radiant heat flux slice plane was orientated in the positive z-direction such that the measurements were taken facing the hot gas layer.

The results of the FDS modeling were imported into Mott MacDonald's STEPS pedestrian modeling software. STEPS used the FDS model to define the road tunnel and vehicle geometries. Iso-surfaces and slices files of visibility and carbon monoxide concentration were read directly into STEPS, and these were used to account for the impact of conditions within the tunnel on pedestrian evacuation.

Finally, a number of people types with different individual characteristics were created and distributed throughout the model dependent on vehicle type.

STEPS is a stochastic model. Therefore each simulation was run five times, reflecting variations in people's behavior. From each run the overall evacuation time, as well as maximum and average FED of carbon monoxide encountered by the evacuating people along the length of their route were calculated. From the worst case run, sample people were selected from each 20-meter section of the tunnel and their progress through the model processed to illustrate the effects of visibility conditions.

MODELED SCENARIO

The general layout of the tunnel is shown in *Figure **10*** at the end of this paper.

The model represents a 416 meter long bidirectional road tunnel that is 9.5 meters wide from wall to wall and 5.5 meters tall from top of road surface to ceiling. The ends of the tunnel are open to the air and are treated as the exit points for the egressing pedestrians. The roadway has a slope of 5.6% for the first 95 meters on the left hand side, with the left hand exit being the highest point. The remainder of the tunnel is level.

The fire is positioned 140 meters from the end of the tunnel in the center of the roadway. The fire is a 30MW fire with a heat release rate illustrated in *Figure **1*** below.

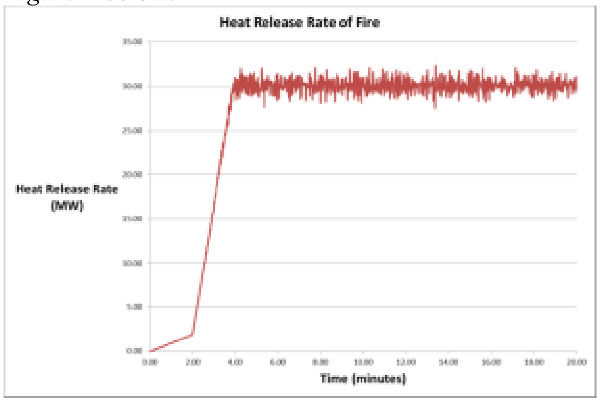


Figure 1: Fire heat release rate.

The tunnel ventilation system is a point extract system, with 4.5 x 2 meter openings at 25 meter intervals in the ceiling that exhaust into a duct above the roadway driven by axial fans located near to the tunnel exits. The openings are opened only in the near vicinity of the fire.

The two cases simulate three openings being open above the fire with two different extraction rates.

Case 1: each of the 3 openings extracts 40 m^3/second, making a total of 120 m^3/second extraction.

Case 2: each of the 3 openings extracts 60 m^3/second making a total of 180 m^3/second extraction.

In both cases, the fans activate at time t=0 (i.e. upon fire ignition).

Note that the complete tunnel ventilation extraction system was not modelled. For simplicity the smoke extraction was modelled as set ventilation extraction points.

Seven different vehicle types were included in the simulation to provide a representative mixture of vehicles that will be in the tunnel. The vehicle occupancy and location is listed in Table 1.

Table 1: Vehicle occupancy and proportion.

Vehicle Type	Vehicle Occupancy	Number of vehicles to left of fire	Number of vehicles to right of fire	Proportion of total vehicles
Private Car	1	3	5	22%
Taxi	2	1	2	8%
Light Goods Vehicle (LGV)	2	2	5	19%
Heavy Goods Vehicle (HGV)	2	2	5	19%
Minivan	5	1	1	5%
Minibus	15	1	2	8%
Bus or Coach	53	2	5	19%

The exits from the buses have been modeled at a width of 0.5 meters, with a flow rate of 0.463p/s, based on the capacity of a stair as indicated in the NFPA 130 standard. This result is that a bus of 53 people takes 114 seconds to empty, or just under two minutes.

PRE-MOVEMENT TIMES

Two methods for the inclusion of pre-movement times were implemented.

The first was the use of a single fixed pre-movement time of five minutes for every person in the simulation. This works on the basis that a serious fire would be detected within approximately two minutes. It would take a further one minute for the operator to investigate the alarm. After this, a combined recognition and response time of two minutes is added for all tunnel occupants to begin moving.

The second method was to add a variable pre-movement time, based on three different probability density functions dependent on the proximity to the fire.

A probability density function describes the likelihood for a random variable at a given time, in this case the likelihood of people to start moving. The area under the graph represents the fraction of people who have started moving up to that time, and therefore must have a total area of 1.

The British Standard PD 7974-6:2004 indicates that the pre-movement time distributions tend to follow a log-normal distribution defined by the following:

- $\Delta t_{pre\ (first\ occupants)}$, which is the time at which the first people begin to move
- $\Delta t_{pre\ (99th\ percentile)}$, which is the time at which 99% of people have begun to move

The curves have been simplified in this study and are applied to the model based on three different zones in the tunnel. This takes into account the fact that people in vehicles further away from the fire may not be aware of the hazardous conditions ahead of them and are therefore less likely to start evacuating promptly, especially since they may be reluctant to leave the apparent safety of their vehicles.

People within 50 meters of the fire have been assigned a pre-movement time distribution as illustrated in *Figure* ***2*** below, ranging from 2 to 8 minutes.

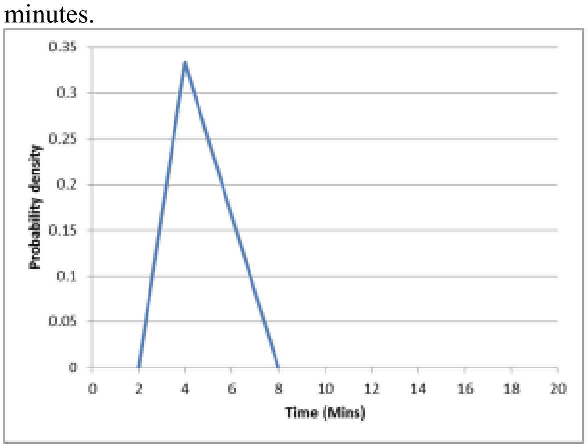


Figure 2: Pre-movement time distribution, 0 to 50 meters from fire.

Those people within 50 to 100 meters of the fire have been assigned a pre-movement time distribution as illustrated in *Figure* ***3*** below, ranging from 3 to 12 minutes.

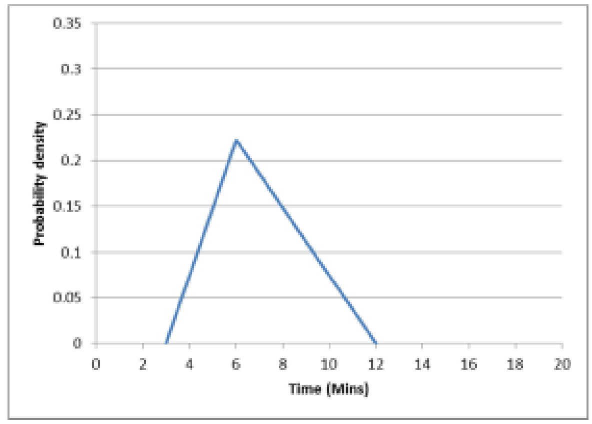


Figure 3: Pre-movement time distribution, 50 to 100 meters from fire.

And finally those people greater than 100 meters from the fire have been assigned a pre-movement time distribution as illustrated in *Figure* ***4*** below, ranging from 4 to 16 minutes.

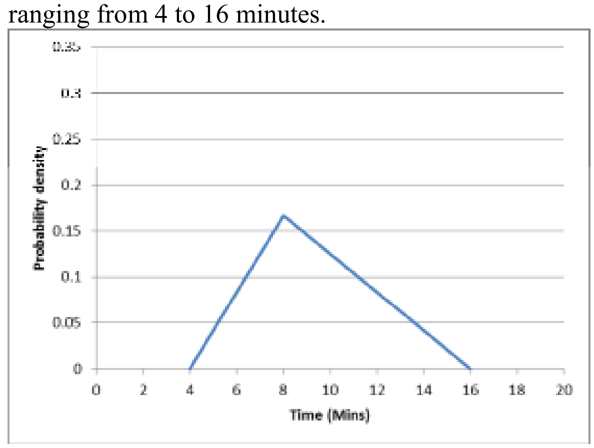


Figure 4: Pre-movement time distribution, greater than 100 meters from fire.

WALKING SPEEDS

Two different walking speed profiles were also examined.

The first was the two fixed speeds:

- 1 m/s for able-bodied people
- 0.5 m/s for people of reduced mobility (PRM).

The second was the application of a probability density to the walking speed to account for the range of people. The bounds were taken from the NFPA 502 standard, with the slowest walking speed being 0.5 m/s and the fastest being 1.5 m/s with a mode of 1.0m/s.

The effect of the visibility conditions on the walking speeds of people was taken into account using the extinction coefficient output from FDS, based on the Jin and Yamada non-irritant gas curve, as illustrated in *Figure* ***5***.

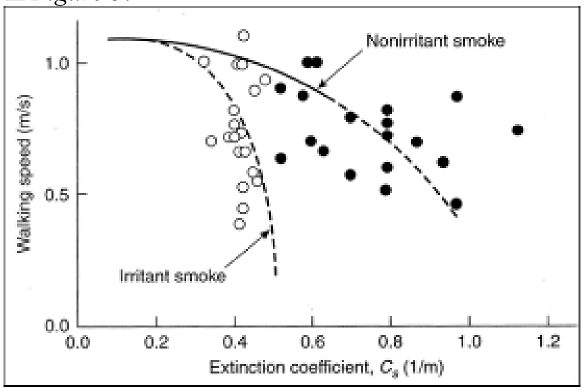


Figure 5: Effect of extinction coefficient on walking speed – Jin & Yamada 1985.

The resulting walking speed is then taken as the slower of either the assumed normal walking speed or the local walking speed, based on visibility conditions. Therefore in the case of a PRM walking at 0.5 m/s the extinction coefficient to speed relationship is only applied below $C_s = 0.9$.

SIMULATION SCENARIOS

A total of four simulation scenarios were set up, taking into account the two fan sizes and the differing application of pre-movement time and walking speeds, as listed in Table 2 below.

Table 2: List of simulations.

Scenario	Total fan capacity	Pre-movement time	Walking speed
Case 1 Fixed	120 m^3/s	5 minutes	1 m/s 0.5 m/s PRM
Case 1 Distribution	120 m^3/s	Distribution	Distribution
Case 2 Fixed	180 m^3/s	5 minutes	1 m/s 0.5 m/s PRM
Case 2 Distribution	180 m^3/s	Distribution	Distribution

ASSESSMENT OF TENABILITY

The assessment of the tenability conditions within the tunnel environment to allow people to evacuate safely considered the following aspects:

Local air temperature

NFPA 502 states that motorists should not be exposed to maximum air temperatures that exceed 60°C (140°F) during emergencies. The threshold of 60°C was therefore taken to be the limit of tenability.

Radiant heat flux from the fire and hot smoke layer

NFPA 502 states that the tenability limit for exposure of skin to radiant heat is approximately 2.5kW/m². Below this heat flux level, exposure can be tolerated for 30 minutes or longer. This corresponds to the temperature of the hot gas layer directly above being greater than approximately 200°C.

Visibility

The effect of smoke on the visibility recorded by individual agents within the environment is taken into account in the STEPS model through the extinction coefficient data from the FDS model, resulting in a reduction on walking speed in low visibility areas.

Carbon monoxide concentration

The tenability of carbon monoxide concentrations was evaluated based on the guidance described in the technical standard ISO/TS 13571:2012(E) "Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires."

The formula stated in the guideline for the calculation of FED for carbon monoxide is this:

$$FED_{CO} = \sum_{t1}^{t2} \left(\frac{\varphi_{CO}}{35000}\right) \Delta t$$

In this formula, φco = average carbon monoxide exposure in ppm over time Δt in minutes.

In this standard, an $FED_{CO} = 1$ corresponds by definition to the median value of a log-normal distribution of responses. At this level of FED, statistically one half of the population will experience tenable conditions with the other half experiencing compromised tenability.

The compromising tenability dose, ($C \cdot t$), for carbon monoxide of 35,000 µliter·liter^{-1}·minutes was obtained from experimentation. The unit µliter·liter^{-1} represents a concentration level that can also be expressed as ppm. Exposure to carbon monoxide is a cumulative effect; therefore a ppm of 35,000 experienced for 1 minute will have the same incapacitating effect as a ppm of 10,000 experienced for 3minutes 30seconds.

The ISO standard further discusses the consideration of threshold criteria and their dependence on the desired design output, providing the following values to help designers chose appropriate levels.

Table 3: FED threshold criteria from ISO/TS 13571.2012(E)

FED threshold criteria	% population susceptible
0.3	11.4%
0.2	5.4%
0.1	1.1%

STATIC EVACUATION TIME CALCULATION

A static calculation considering the worst case positioning of people in the fixed pre-movement and walking speed scenario can provide an indicative time required for evacuation of the tunnel, both with and without PRMs.

As indicated in *Figure **10***, the position from which it takes the longest to evacuate from the tunnel is the rear of the closest coaches on either side of the fire, assuming that the last person exiting the coach descends 2 minutes after the first person to move. This time is further increased if the last person to leave is a PRM.

The distances required to walk to safety at the tunnel exit is 109 meters to the left of the fire, and 255 meters to the right.

Using the same parameters as in the fixed STEPS case, i.e., an able-bodied walking speed of 1 m/s, a PRM walking speed of 0.5 m/s, a pre-movement time of 5 minutes, and 2 minutes taken to empty a bus, the calculated static evacuation times are as listed in Table 4 below.

Table 4: Static spreadsheet evacuation time calculation.

	Evacuation time (min:sec)			
	To the left of the fire		To the right of the fire	
Pedestrian type	Able-bodied	PRM	Able-bodied	PRM
Pre-movement time	5:00	5:00	5:00	5:00
Time to descend from bus	2:00	2:00	2:00	2:00
Time to walk	1:49	3:38	4:15	8:30
Total Time	**8:49**	**10:38**	**11:15**	**15:30**

RESULTS

Temperature

In order to assess the tenability of temperature in the tunnel, temperature plots were taken directly from FDS at a height on 2.5 meters from the roadway at one-minute intervals for each fan size case. The resulting plots are shown in *Figure **11*** and *Figure **12*** at the end of this paper.

The plots start with time T = 1 minute at the top ranging to time t=20 minutes at the bottom. The distances 50 and 100 meters from the fire are marked. At the height of 2.5 meters only the larger Heavy Goods Vehicle (HGV) and Coaches cut through the slice plane, and hence are the only vehicles visible in the plot.

The plots for fan Case 1, the lower fan size of 3 x 40 m^3/s, show that conditions deteriorate more on the left-hand side of the tunnel, where the temperature is over 60 Celsius between 5 and 6 minutes into the simulation. There is also an area just inside the left-hand side tunnel entrance where a spike in temperature occurs 7 minutes into the simulation.

When considering temperatures for Case 1 to the left of the fire, both the zones 0 to 50 and 50 to 100 meters become untenable for evacuation 6 minutes into the simulation. In the left-hand area 100 meters from the fire and beyond the area of temperature above 60 Celsius near the tunnel entrance appears 7 minutes into the simulation and then fluctuates throughout the rest of the simulation. The area around the last HGV becomes untenable at 8 minutes into the simulation.

To the right of the fire, the zone from 0 to 50 meters from the fire becomes untenable 5 minutes into the simulation. The remaining zones are tenable throughout the simulation.

The plots for fan Case 2, the higher fan size of 3 x 60 m^3/s, indicate that the extents of the area where the temperature is over 60 Celsius is more limited and takes longer to reach its maximum extents. There is still an area just inside the left-hand side tunnel entrance where a spike in temperature occurs.

When considering temperatures for Case 2 to the left of the fire, the zone 0 to 50 becomes untenable for evacuation 4 minutes into the simulation and the section 50 to 100 meters 10 minutes into the simulation. In the left-hand area situated 100 meters and beyond from the fire, an area of temperature above 60 Celsius appears near the tunnel entrance 10 minutes into the simulation and then fluctuates throughout the rest of the simulation. The area around the last HGV becomes untenable at 12 minutes into the simulation.

To the right of the fire, the temperature in the zone 0 to 50 meters from the fire reaches 60 Celsius 4 minutes into the simulation, with the remaining sections being tenable throughout the simulation.

These results are summarized in Table 5 and Table 6 below.

Table 5: Times at which temperature exceeds 60 Celsius to the left of the fire.

Fan Case	**Time at which temperature exceeds 60 Celsius in sections to left of fire (mins:secs)**		
	0 to 50 m from fire	**50 to 100m from fire**	**Greater than 100m from fire**
1	5:30	5:15	Partial at 6:00
2	4:00	9:30	Partial at 10:00 to 12:00

Table 6: Times at which temperature exceeds 60 Celsius to the right of the fire.

Fan Case	**Time at which temperature exceeds 60 Celsius in sections to right of fire (mins:secs)**		
	0 to 50 m from fire	**50 to 100m from fire**	**Greater than 100m from fire**
1	5:00	Remains tenable	Remains tenable
2	4:30	Remains tenable	Remains tenable

Heat flux

The results from the FDS files indicated that, aside from the immediate vicinity of the fire, at no time does the heat flux exceed the 2.5kW/m² value cited in the NFPA 502 standard.

A summary of the maximum radiant heat flux recorded on the slice plane facing upwards towards the hot gas layer in each section for both fan cases, excluding the area of the fire is presented in Table 7 and
Table 8.

Table 7: Maximum heat flux to the left of the fire.

Fan Case	**Maximum heat flux to left of fire (kW/m2)**		
	0 to 50 m from fire	**50 to 100m from fire**	**Greater than 100m from fire**
1	1.11	0.36	0.21
2	1.01	0.27	0.14

Table 8: Maximum heat flux to the right of the fire.

Fan Case	**Maximum heat flux to right of fire (kW/m2)**		
	0 to 50 m from fire	**50 to 100m from fire**	**Greater than 100m from fire**
1	1.14	0.10	0.03
2	1.14	0.02	0.00

Visibility

The total evacuation time, which indicates the impact of the extinction coefficient on the occupants of the tunnel, are listed in Table 9 below, as averaged across the 5 separate runs undertaken for each scenario, along with a comparison to the time derived from the static calculation where a PRM is the last person to exit the tunnel.

Table 9: Total evacuation time, averaged over the 5 separate runs undertaken for each scenario.

Scenario	**Total evacuation time (mins:secs)**	**% increase over static PRM calculation**
Static Calculation	15:30	-
Case 1 Fixed	17:34	+13%
Case 1 Distribution	18:50	+22%
Case 2 Fixed	16:24	+6%
Case 2 Distribution	18:43	+21%

All STEPS simulations provide a longer evacuation time than the static evacuation time, highlighting the impact the extinction coefficient has on the walking speeds of people in the STEPS model.

Both the fixed scenarios have closer times to the static calculation since the pre-movement times are fixed, and therefore the only factor that can affect the overall time is the extinction coefficient slowing the walking speeds of the people in the simulation. The Case 2 fixed is the closest to the static calculation, providing indication that the increase in fan size improved visibility along the evacuation route.

The two distribution scenarios have significantly longer and comparable evacuation times due to the variable pre-movement times of up to 16 minutes in the areas beyond 100 meters from the fire. For these scenarios, the beneficial impacts of a larger fan size are not obvious when considering the total overall tunnel evacuation time. The pre-movement time assumptions result in a recorded reduction of only 7 seconds to the overall tunnel evacuation time with the larger fan size. In order to understand better the differences between the two scenarios further analysis of the results is required.

The times taken to evacuate the section within 50 meters of either side of the fire, and then the two subsequent 50-meter sections of the tunnel are shown in Table 10 and Table 11 below.

Table 10: Evacuation times of sections of tunnel to the left of the fire.

Scenario	**Time for section to the left of the fire to be evacuated (mins:secs)**		
	0 to 50 m from fire	**50 to 100m from fire**	**Greater than 100m from fire**
Case 1 Fixed	7:51	10:43	12:47
Case 1 Distribution	9:27	13:20	16:10
Case 2 Fixed	7:51	10:43	12:56
Case 2 Distribution	9:30	13:13	16:00

Table 11: Evacuation times of sections of tunnel to the right of the fire.

Scenario	**Time for section to the right of the fire to be evacuated (mins:secs)**		
	0 to 50 m from fire	**50 to 100m from fire**	**Greater than 100m from fire**
Case 1 Fixed	9:00	11:27	17:34
Case 1 Distribution	12:18	14:52	18:57
Case 2 Fixed	8:40	10:24	16:24
Case 2 Distribution	12:00	12:57	18:47

While providing more detailed information, the results still do not indicate any significant advantage with the increase in fan size.

In order to provide further information, the routes of individual people were tracked through each of the simulations. The people selected represented the likely worst-case starting position in each of the 20-meter sections along the tunnel.

The position along the tunnel of these people is represented as a line graph, with their position along the tunnel on the x-axis and time on the y-axis. Each end of the x-axis represents the exits of the tunnel, with the fire location represented in the center as a red vertical line. The period of pre-movement time therefore appears as a vertical line, since that time there is no movement along the tunnel. Once the people begin moving, their line inclines along their exit path. In the case of people at the back of a coach or in a minibus, this will result in them walking towards the front of the vehicle they are in and therefore away from the tunnel exit they will be using. The shallower the line is, the quicker the people are walking. It is therefore possible to track their speed change due to low visibility by looking at changes in the gradient of the line. Finally two orange dashed lines indicated the path of the clearance time on each side.

The resulting plots for the two fixed scenarios are displayed in *Figure **6*** and *Figure 7* below.

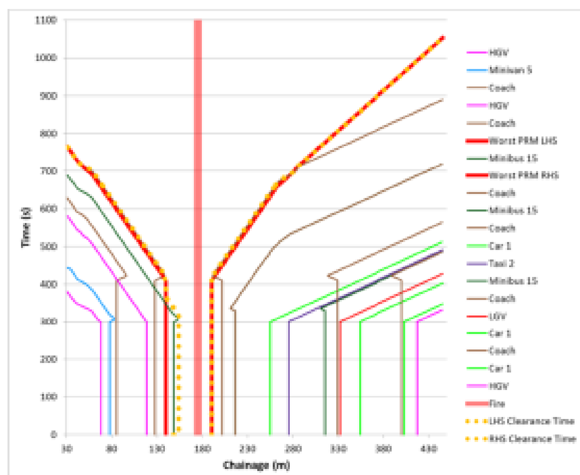


Figure 6: Routes of selected people during Case 1 Fixed scenario.

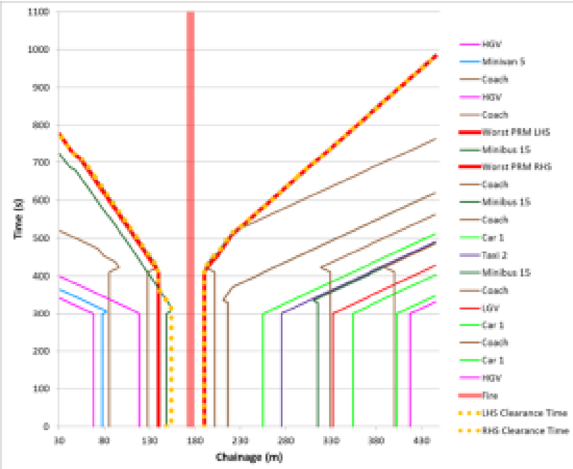


Figure 7: Routes of selected people during Case 2 Fixed scenario.

A comparison of *Figure* ***6*** and *Figure 7* indicates that to the left of the fire, the four people closest to the left tunnel exit walk more quickly with the higher fan size, with fewer changes in speed, as indicated by their flatter graphs. The remaining three people to the left of the fire, including the worst-case PRM on the coach, are still affected by the smoke, resulting in the same overall evacuation times. It is worth noting that the able-bodied person exiting the coach is moving at roughly the same speed as the PRM on the same coach, indicating that the effects of smoke is causing their walking speed to be halved.
To the right of the fire, those 9 people closest to the right tunnel exit move through both simulations with limited different in their movement between the two fan sizes. The remaining 3 people are less affected by smoke with the larger fan size. This can be seen where the walking speeds of the last person and PRM exiting the coach increase in Case 2 Fixed at a chainage of around 220 meters, a change that occurs some 65 meters later in Case 1 Fixed, at around 285 meters.

The resulting plots for the two distribution scenarios are displayed in *Figure* ***8*** and *Figure* ***9*** below.

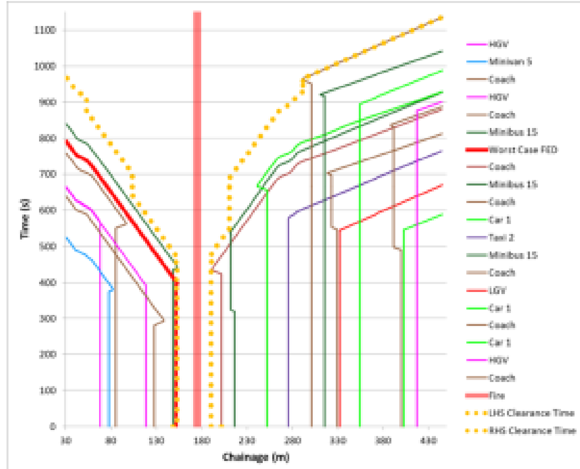


Figure 8: Routes of selected people during Case 1 Distribution scenario.

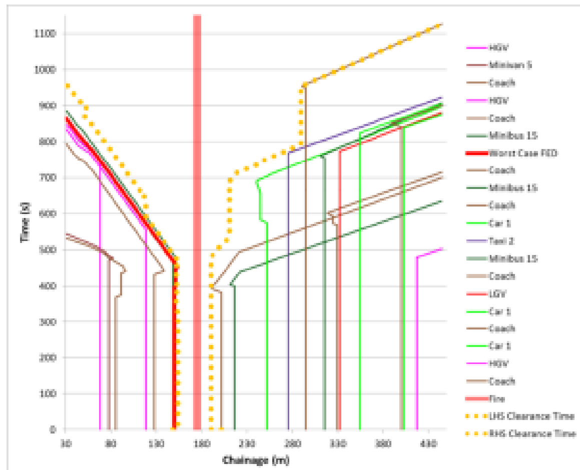


Figure 9: Routes of selected people during Case 2 Distribution scenario.

The impact of the variable pre-movement times is immediately apparent, with the variance of the length of the initial static period.

The difference in the impact of the two fan sizes on the people's movements is similar to that seen in the fixed cases. The two people who move early nearest the left end of the tunnel again exit the tunnel faster with the larger fans in place. Those who linger longer, or are closer to the fire on the left-hand side, are still affected by the smoke in the larger fans scenario, though they do exit slightly before those in the smaller fans scenario.

To the right of the fire, while the overall evacuation time is not changed significantly, this is caused by a long pre-movement time for a person on a coach, something independent of fan size. What can be seen, however, as with the fixed cases, is that when they do begin to move, the people on the right of the fire are affected less by the smoke, as indicated by their flatter graphs, resulting in quicker evacuation times for them.

Carbon monoxide FED

The maximum and average carbon monoxide FED recorded in each scenario, again averaged over the 5 separate runs undertaken, are listed in Table 12 below.

Table 12: Maximum and average carbon monoxide FED as averaged over the 5 separate runs undertaken for each scenario.

Scenario	Maximum Carbon Monoxide FED	Average Carbon Monoxide FED
Case 1 Fixed	0.0312	0.0065
Case 1 Distribution	0.0246	0.0062
Case 2 Fixed	0.0248	0.0023
Case 2 Distribution	0.0220	0.0028

All the recorded FED values, whether maximum or average are well below 0.1, meaning that significantly less than 1.1% of the population would be susceptible to the effects of carbon monoxide.

In all scenarios, the maximum FED was recorded by the last passenger exiting the coach nearest to the fire.

When comparing the two fixed cases, the increased fan size in Case 2 reduces the maximum CO FED by 20%, and reduces the average CO FED by 65% of those recorded in Case 1 Fixed.

Comparing the two distribution cases, the increased fan size in Case 2 reduces the maximum CO FED by 10%, and reduces the average CO FED by 55% of those recorded in Case 1 Distribution.

CONCLUSIONS

The study indicates that a number of factors need to be assessed when considering tenability conditions for people evacuating a tunnel in the event of a fire.

Of the 4 factors considered for this tunnel configuration, temperature rise affected the tenability of the tunnel environment the quickest. The left-hand side of the tunnel experiences the highest temperatures, with the section of the tunnel 50 meters either side of the fire becoming untenable from 4 to 6 minutes of the start of the simulation.

Ventilation strategy affects how quickly the tunnel environment becomes untenable. The larger fan size Case 2 contains the area where the temperature increases over 60 Celsius into a smaller area than the smaller fan size Case 1 does. The expansion of this area is also slowed with the larger fan Case 2. Both these factors allow for a longer period during which the temperature conditions are tenable for evacuation, indicating the benefit of the increased extraction rate.

Analysis of the remaining 3 factors investigated, namely radiative heat flux, carbon monoxide FED and extinction coefficient, indicate that none of these factors individually exceed the guidelines for the tenability of the tunnel environment in an evacuation scenario. Since, however, the results indicate that the environment in the tunnel is likely to become untenable when considering temperature; it is the temperature that is the limiting factor.

The use of advanced pedestrian modeling software, such as STEPS, which has the ability to import directly files from CFD software such as FDS, allows the assessment of FED and the impact of varying visibility levels, as well as readily permitting different scenarios to be simulated, including changes to walking speeds and pre-movement times. As seen in this study, global parameters do not necessarily provide a full picture of the benefits of different ventilation solutions, such as increases in fan size.

Advanced agent-based pedestrian modeling software can consider the experience of individuals throughout the simulation, providing more information on the performance of different strategies. In this example study, the differing effects of the extinction coefficient on walking speeds between the two fan cases was not readily apparent in the overall evacuation times. The ability to track individual people throughout the simulation demonstrated clear differences in the performance of the two cases.

The study also highlighted the impact of various assumptions on the simulation results. While perhaps not producing the most realistic of scenarios, the use of fixed pre-movement times and walking speeds allows a more direct comparison of the effects of ventilation strategy on tenability. The use of distributions of walking speeds and pre-movement times may provide an arguably more realistic scenario, but it can mask the effects of changes in fan size. A combination of both, as undertaken here, provides a more complete view of the environment that may be experienced in the evacuation.

REFERENCES

National Fire Protection Association (2014), "NFPA 502 Standard for Road Tunnels, Bridges and Other Limited Access Highways," A.7.16.6.3 p. 32, B.2.1 Heat Effects p. 36, B.3 Geometric Considerations p. 38, C.2 Air Temperature Criteria p. 38.

National Fire Protection Association (2014), "NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems," 5.3.5.3 (1) p. 14.

BSI (2004), "PD 7974-6:2004 The application of fire safety engineering principles to fire safety design of buildings."

ISO (2012), "ISO 13571:2012(E) Life-threatening components of fire – Guidelines for the estimation of time to compromise tenability in fires," 6.1.2 p. 6, A.5.2 Accommodating susceptible subpopulations p.18.

Jin, T and Yamada, T., "Irritating Effects of Fire Smoke on Visibility," Fire Science and Technology Vol 5 No 1, 1985.

National Institute of Standards and Technology (NIST), U.S, Department of Commerce, Gaithersburg, Maryland, USA, (2012), "Fire Dynamics Simulator (Version 6.0.1)", Floyd, J., Forney, G., Hostikka, S., Kornhonen, T., Macdermott, W., & McGrattan, K.

Mott MacDonald, STEPS Software (2014), Version 5.3, http://www.steps.mottmac.com

TUNNEL LAYOUT

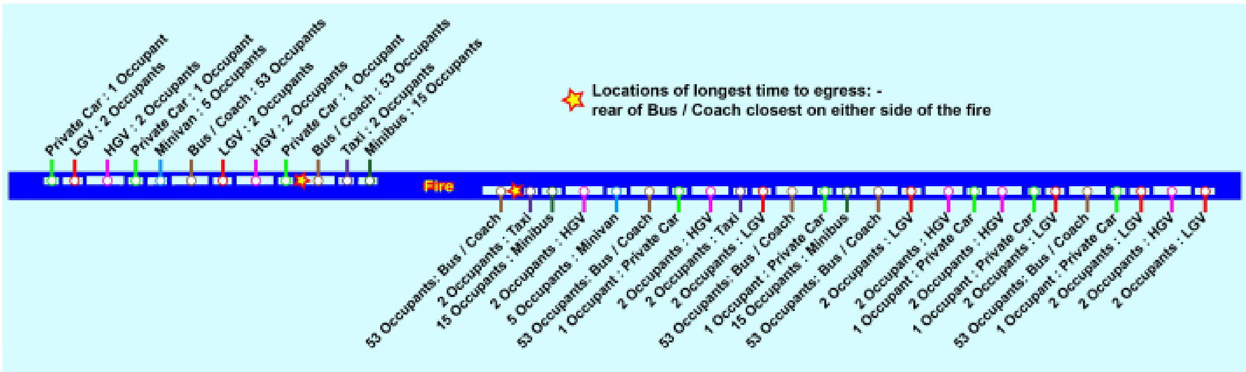


Figure 10: Tunnel layout and vehicle location with occupancy shown.

FDS TEMPERATURE PLOTS

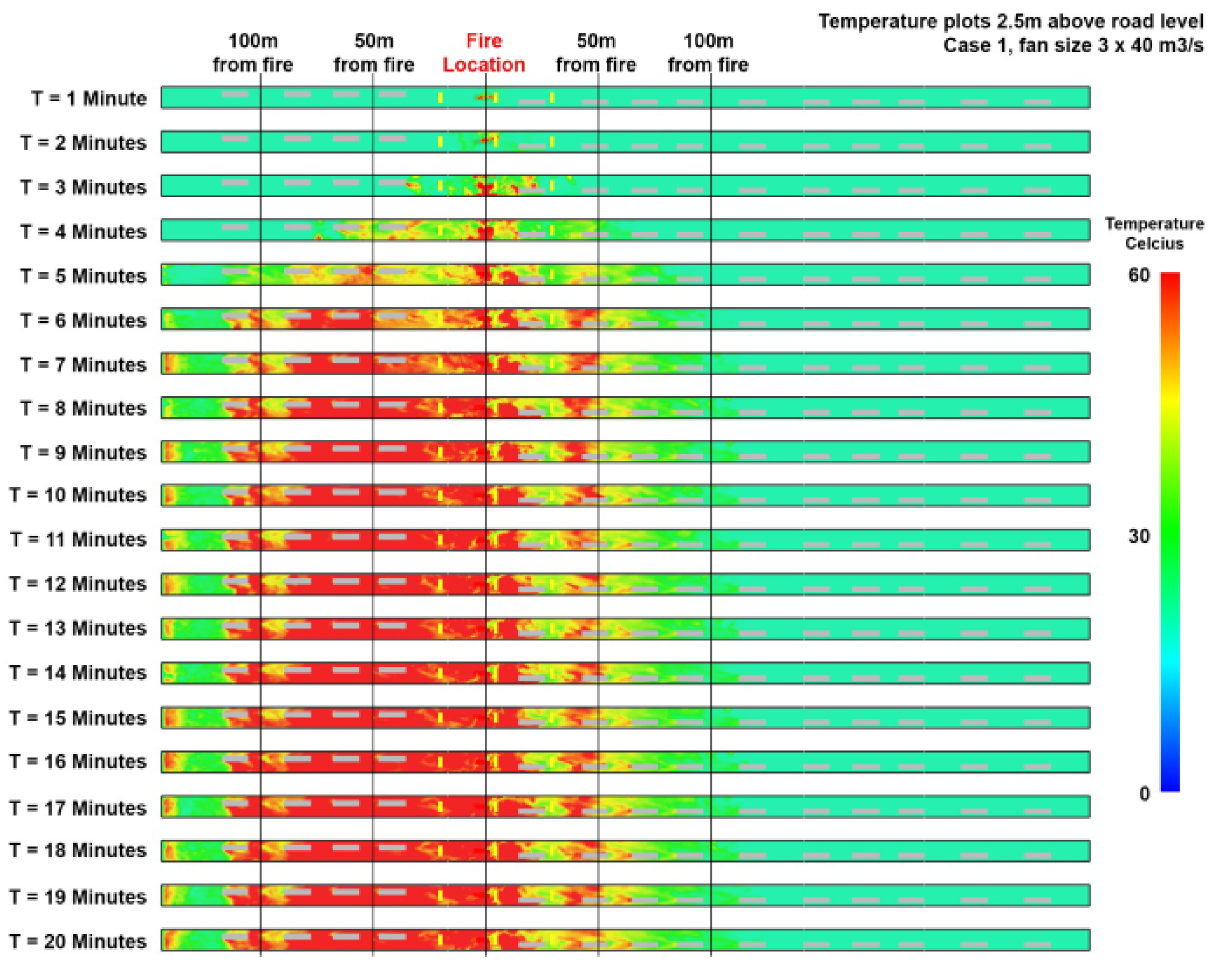


Figure 11: Temperature plots at a height of 2.5m above road level for Case 1, fan size 3 x 40 m^3/s from time = 1 to 20 minutes.

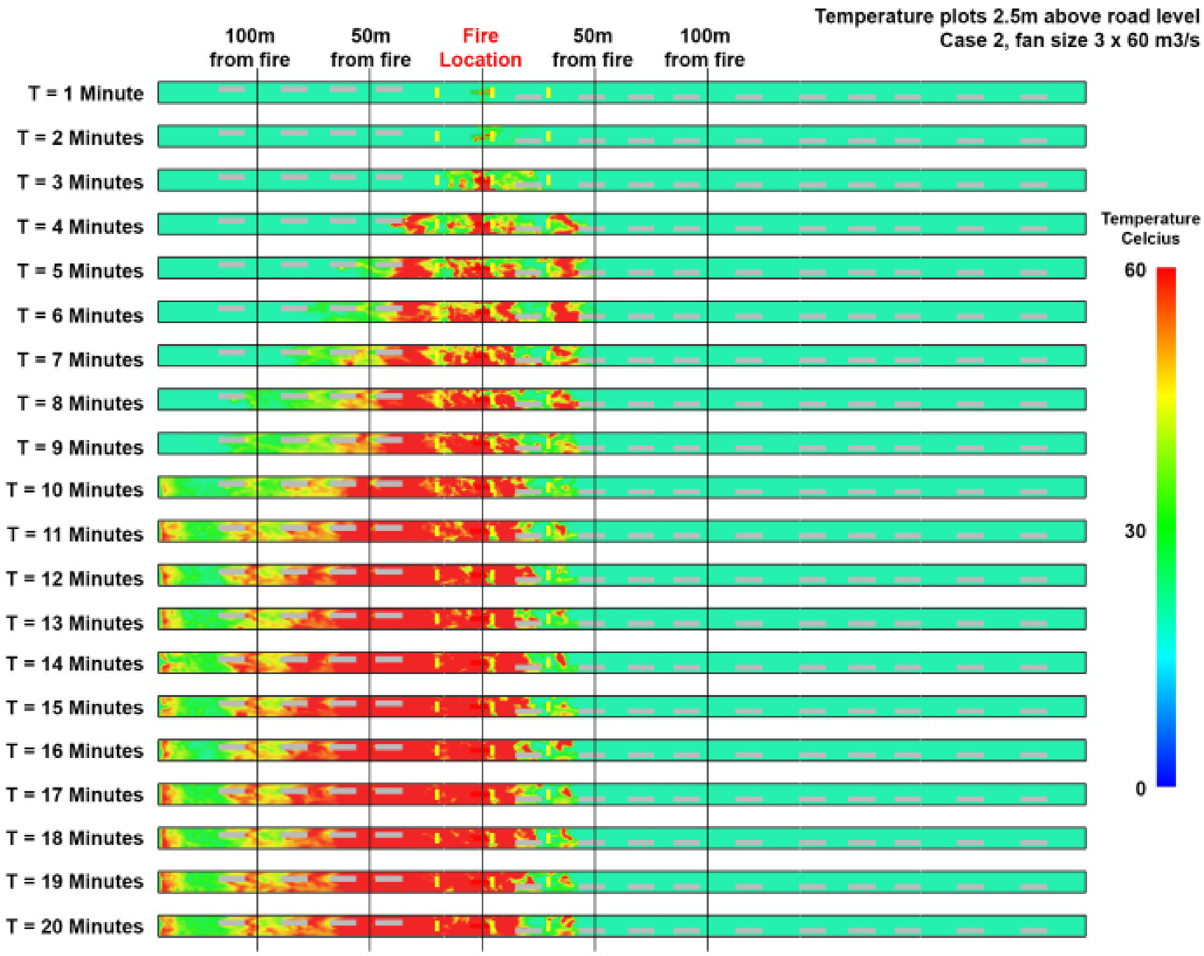


Figure 12: Temperature plots at a height of 2.5m above road level for Case 2, fan size 3 x 60 m^3/s from time = 1 to 20 minutes.

STEPS SIMULATION PLOTS SHOWING EXTINCTION COEFFICIENT

The following represent plots taken from STEPS from the worst case of the five runs of each scenario. The people are represented by pink blocks.

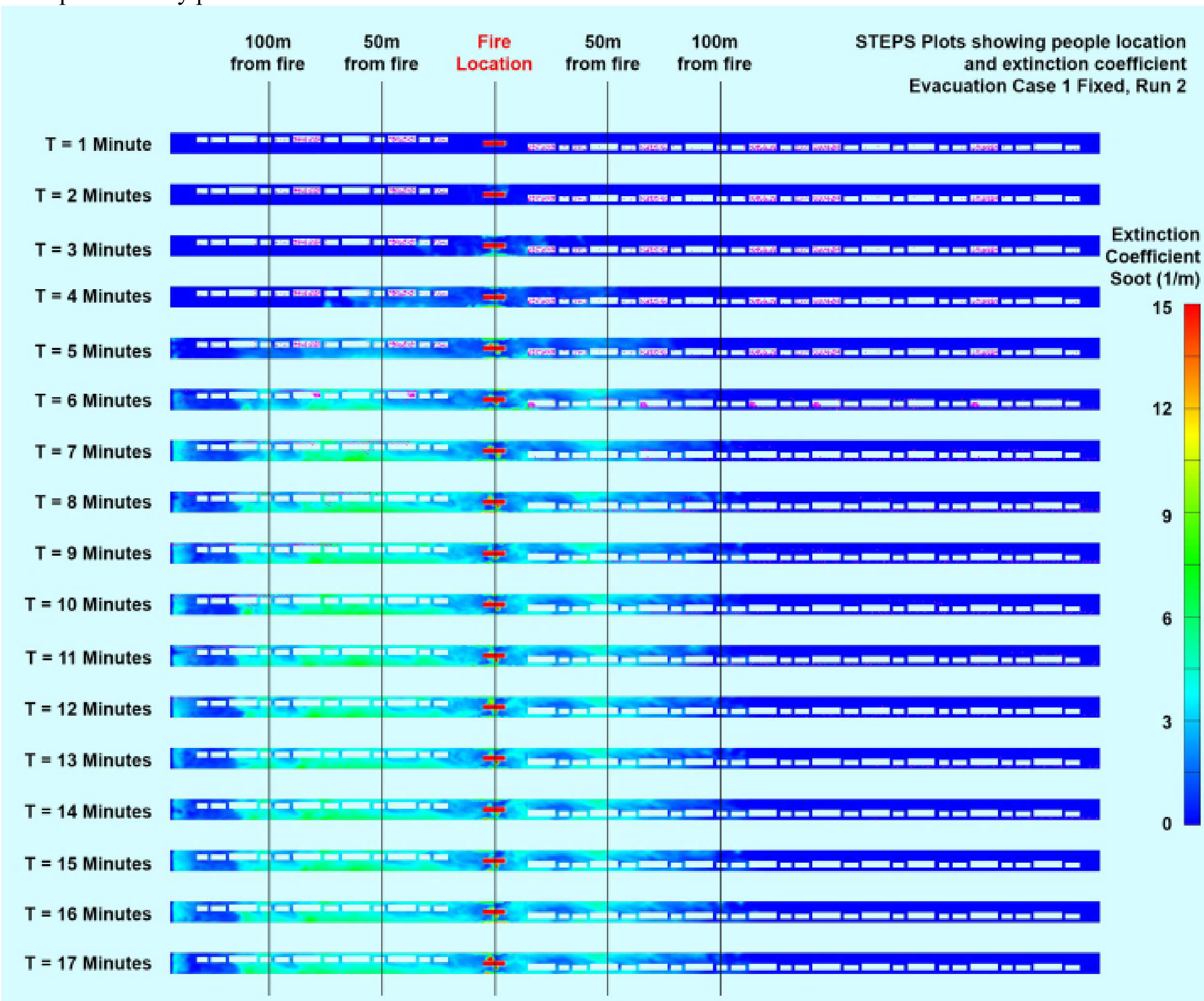


Figure 13: STEPS plots showing people and extinction coefficient during evacuation of Case 1 Fixed. The images are taken from the second run of the simulation.

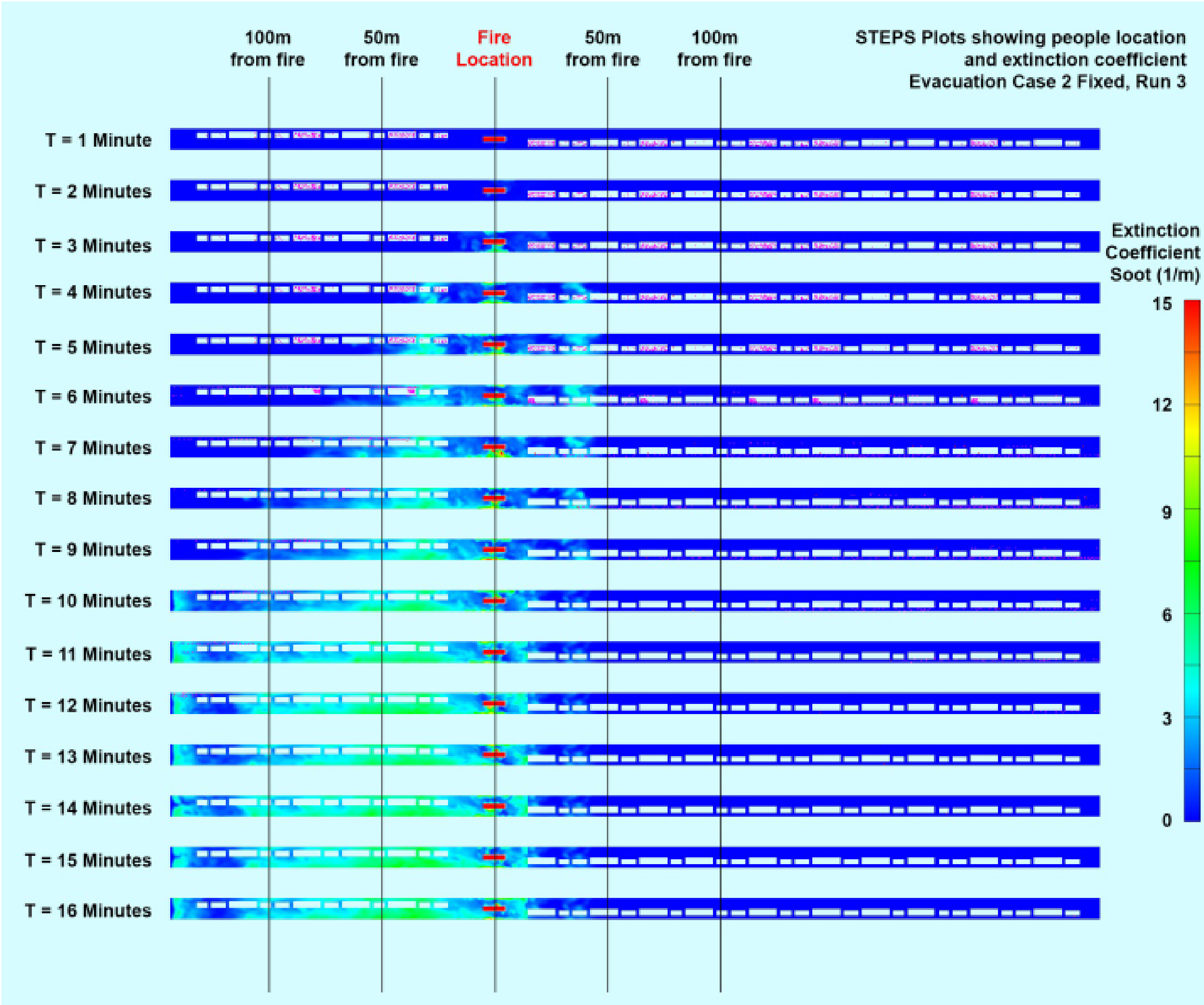


Figure 14: STEPS plots showing people and extinction coefficient during evacuation of Case 2 Fixed. The images are taken from the third run of the simulation.

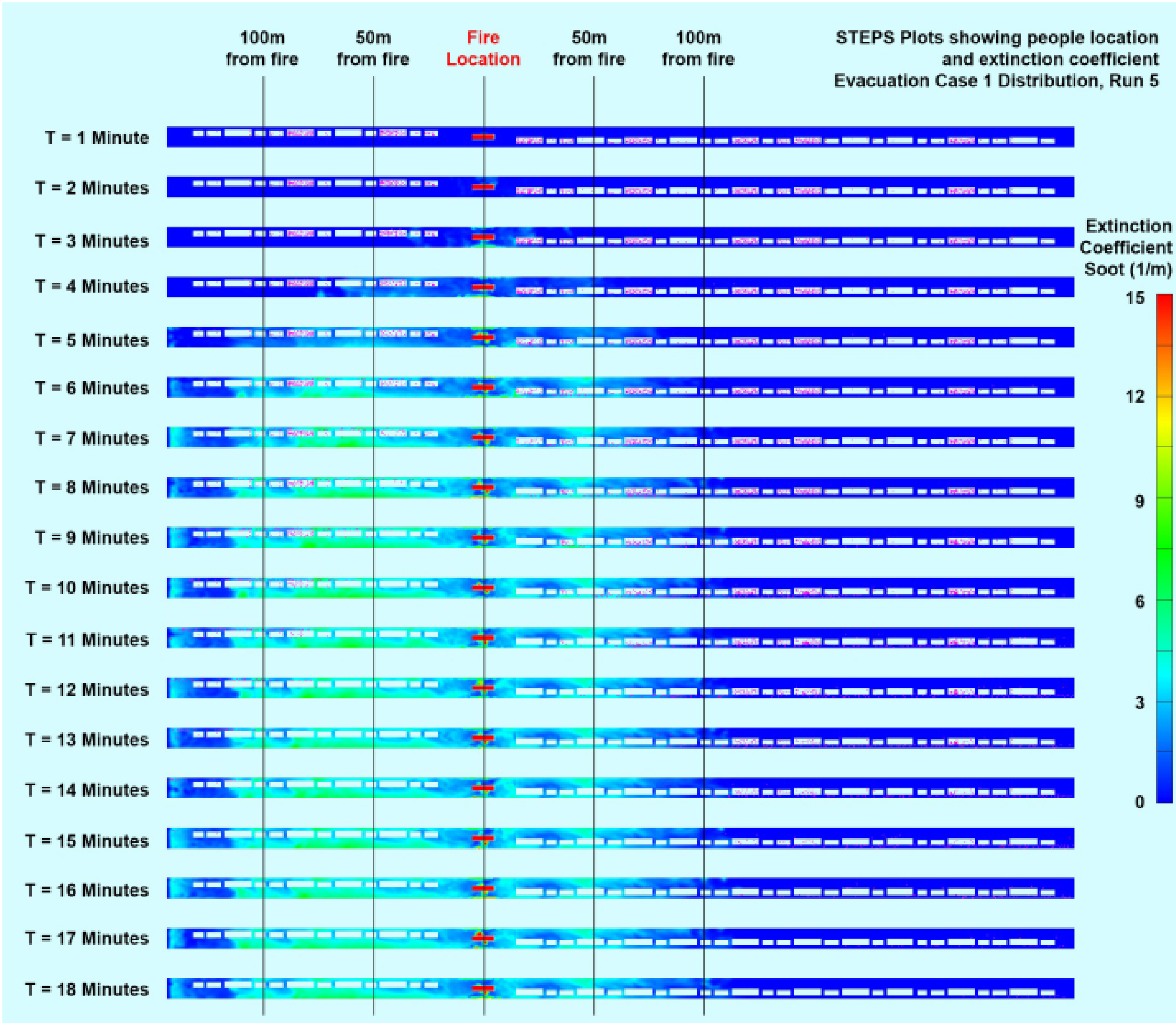


Figure 15: STEPS plots showing people and extinction coefficient during evacuation of Case 1 Distribution. The images are taken from the second run of the simulation.

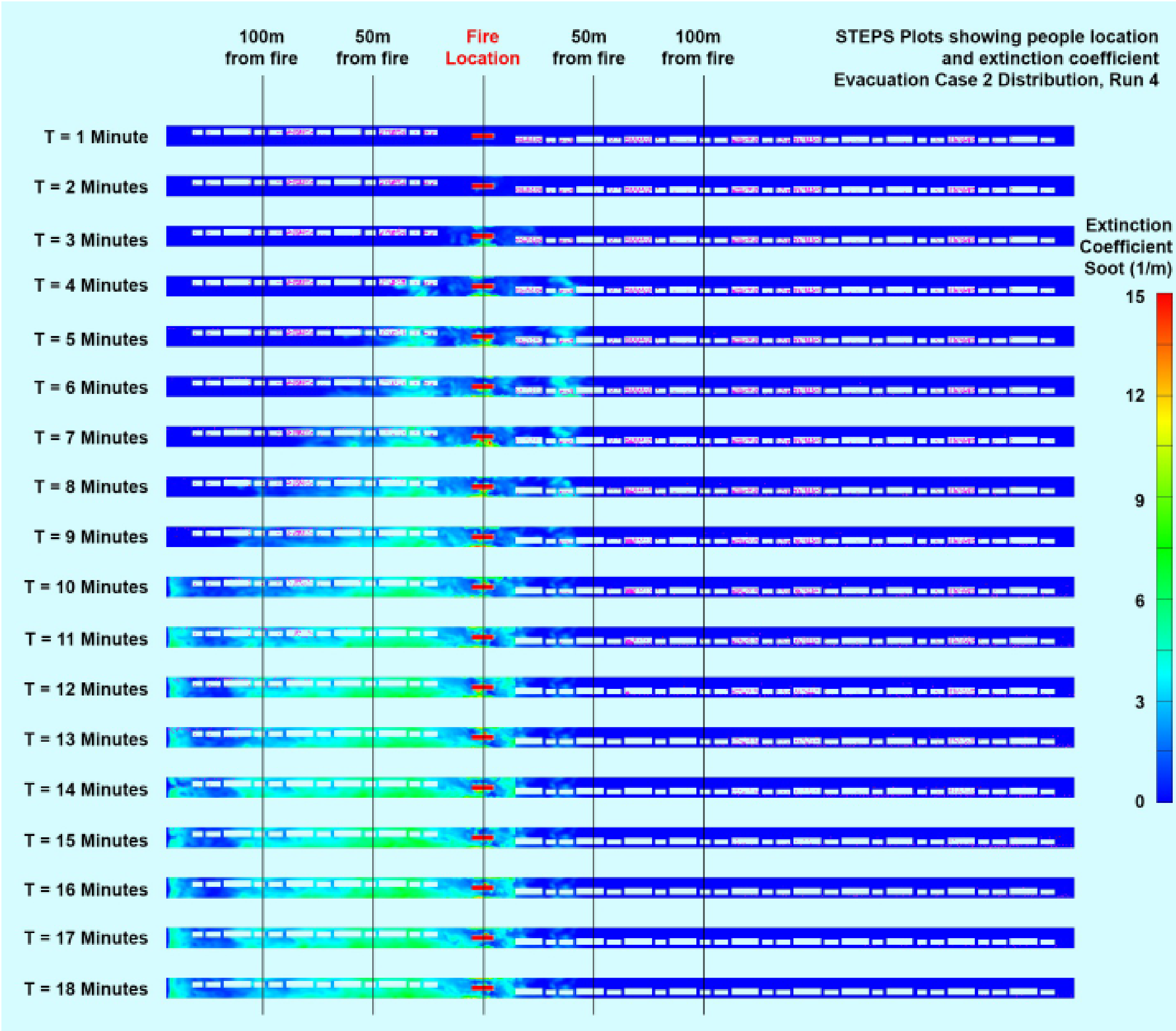


Figure 16: STEPS plots showing people and extinction coefficient during evacuation of Case 2 Distribution. The images are taken from the second run of the simulation.

FDS TEMPERATURE VERTICAL PLANE PLOTS

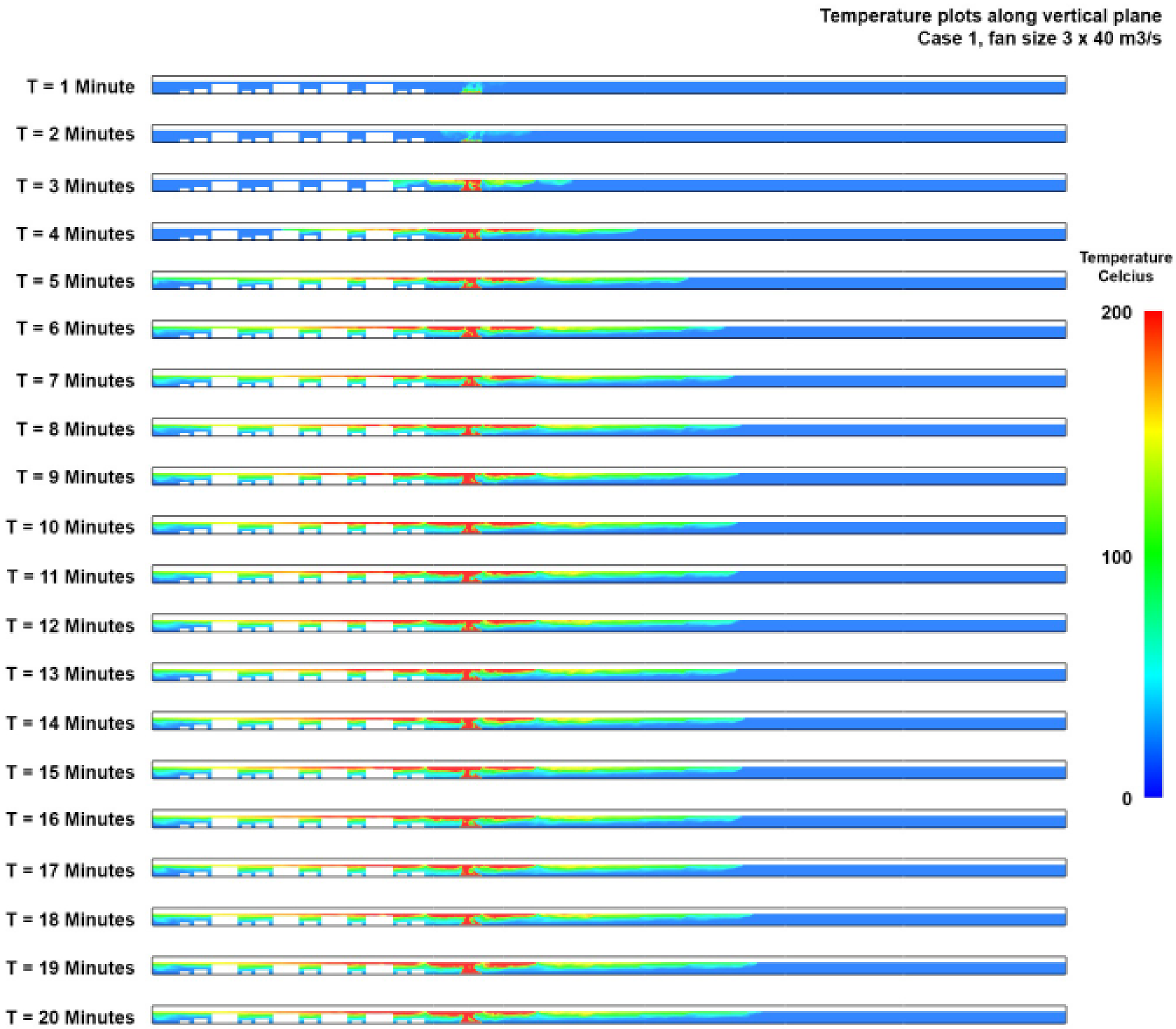


Figure 17: FDS plots of temperature on a vertical plane along the tunnel with Case 1 fans.

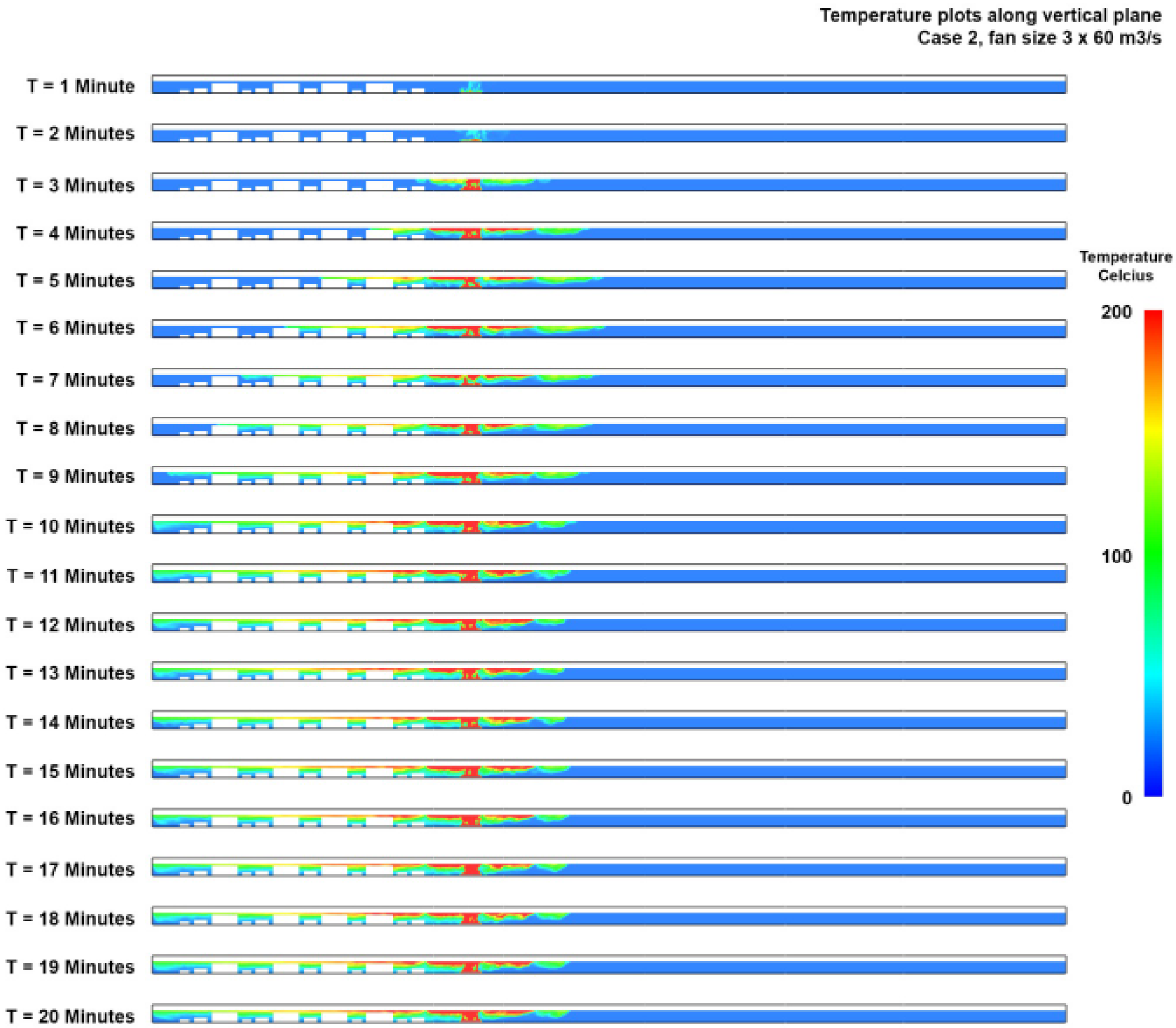
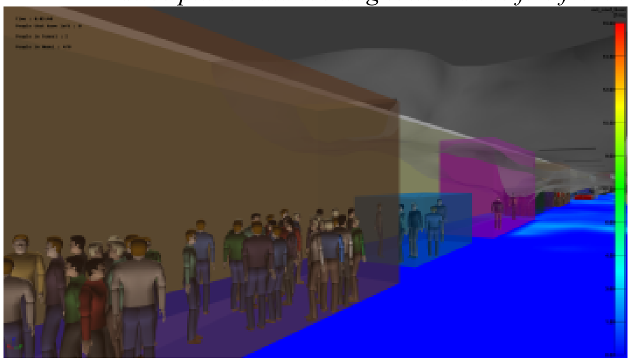
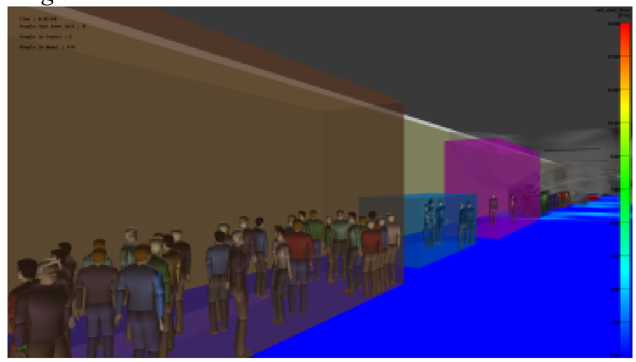


Figure 18: FDS plots of temperature on a vertical plane along the tunnel with Case 2 fans.

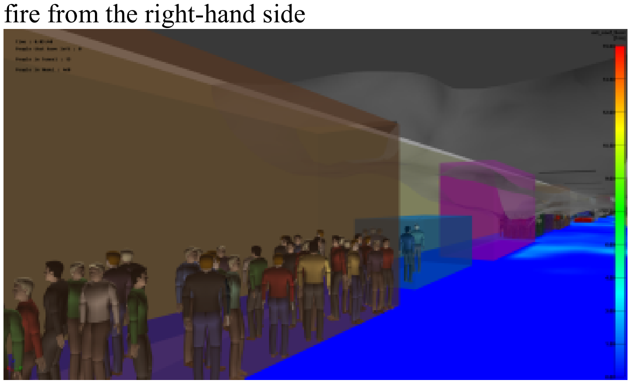
Table 13: Images of the evacuation taken from STEPS with 10 meter visibility iso-surface and extinction coefficient slice plane data looking towards the fire from the right-hand side.



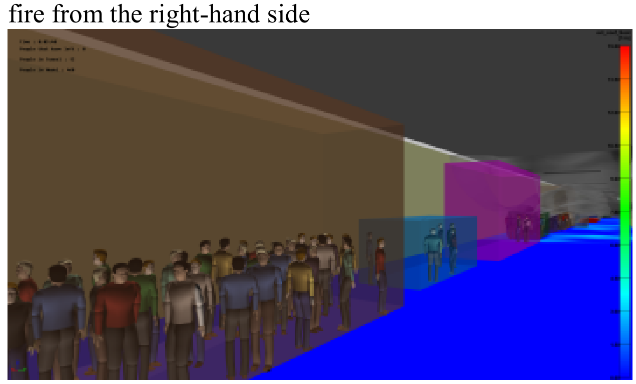
Case 1 Fixed, Time = 3:40 minutes looking towards the fire from the right-hand side



Case 2 Fixed, Time = 3:40 minutes looking towards the fire from the right-hand side



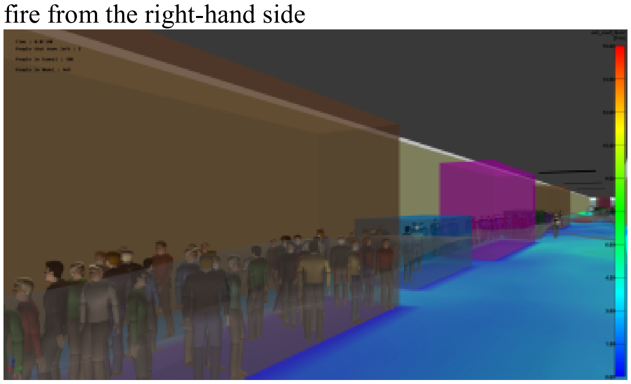
Case 1 Distribution, Time = 3:40 minutes looking towards the fire from the right-hand side



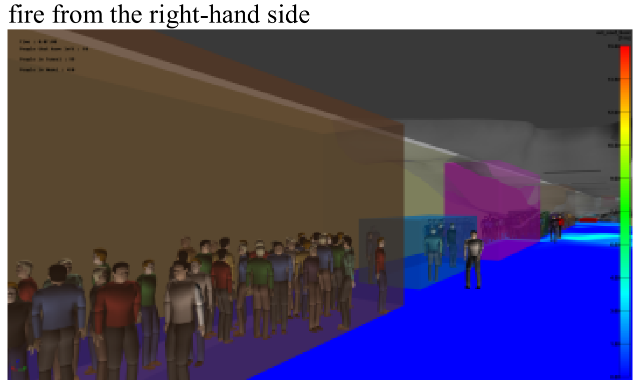
Case 2 Distribution, Time = 3:40 minutes looking towards the fire from the right-hand side

Case 1 Fixed, Time = 7:00 minutes looking towards the fire from the right-hand side

Case 2 Fixed, Time = 7:00 minutes looking towards the fire from the right-hand side

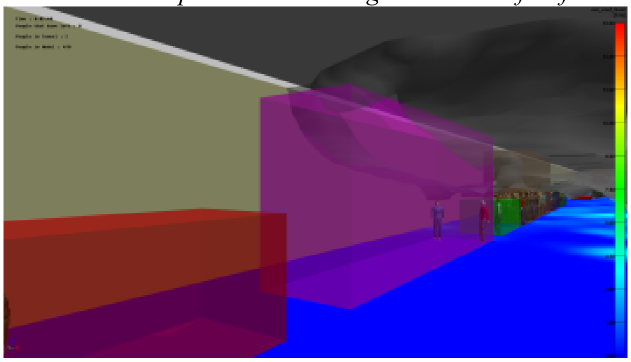


Case 1 Distribution, Time = 7:00 minutes looking towards the fire from the right-hand side

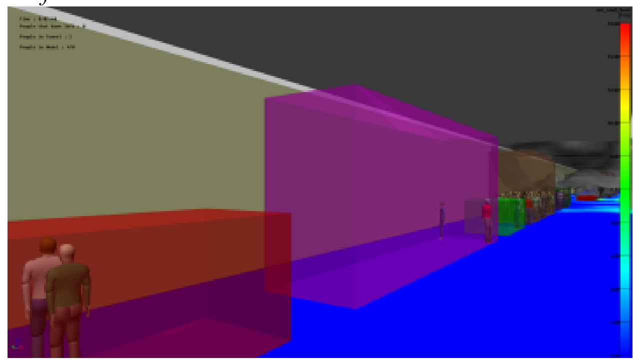


Case 2 Distribution, Time = 7:00 minutes looking towards the fire from the right-hand side

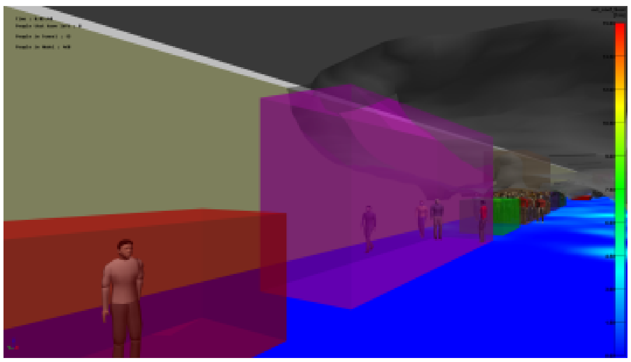
Table 14: Images of the evacuation taken from STEPS with 10 meter visibility iso-surface and extinction coefficient slice plane data looking towards the fire from the left-hand side.



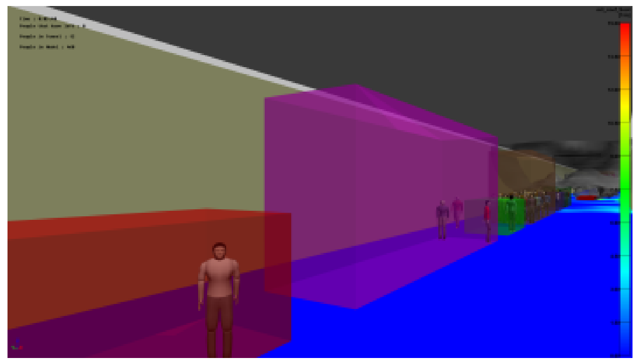
Case 1 Fixed, Time = 3:40 minutes looking towards the fire from the left-hand side



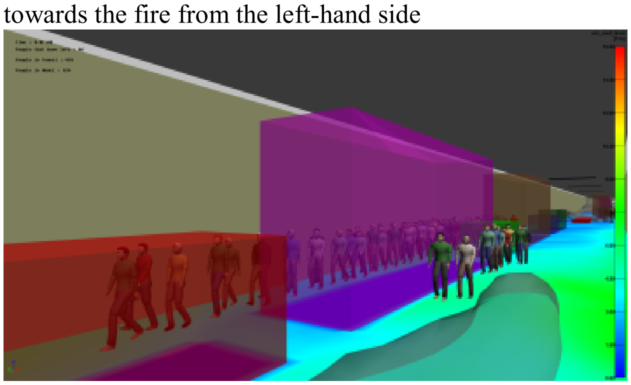
Case 2 Fixed, Time = 3:40 minutes looking towards the fire from the left-hand side



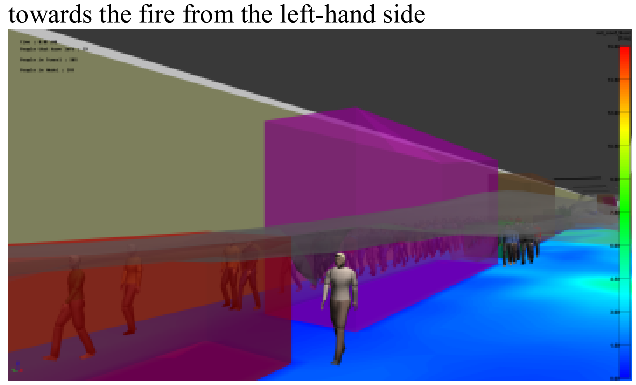
Case 1 Distribution, Time = 3:40 minutes looking towards the fire from the left-hand side



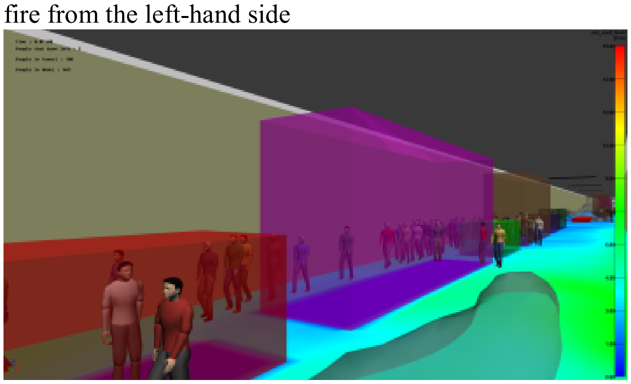
Case 2 Distribution, Time = 3:40 minutes looking towards the fire from the left-hand side



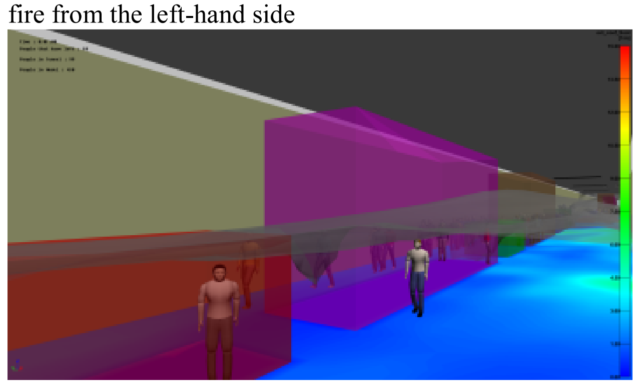
Case 1 Fixed, Time = 7:00 minutes looking towards the fire from the left-hand side



Case 2 Fixed, Time = 7:00 minutes looking towards the fire from the left-hand side



Case 1 Distribution, Time = 7:00 minutes looking towards the fire from the left-hand side



Case 2 Distribution, Time = 7:00 minutes looking towards the fire from the left-hand side