Optimal fire ventilation at congested traffic

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Abstract
The optimal longitudinal ventilation in case of fire following congested traffic is examined. As people are caught on both sides of the fire, the optimal longitudinal velocity is not evident. High flow velocities ensure a smoke-free path upstream of the fire and dilute the smoke but render it impossible for the people downstream to avoid being captured in smoke. On the other hand, at low flow velocities the maximum concentration of toxic gases is higher leading to larger regions with immediately untenable conditions.

1 PREVIOUS VENTILATION PHILOSOPHY

For the longitudinal smoke ventilation in tunnels with congested or bi-directional traffic, PIARC (1) recommends to keep the air velocity low during the evacuation phases. According to the Swiss guideline on tunnel ventilation, the flow velocity should be as small as possible at the location of the fire (2). Contrarily, the Austrian guideline on tunnel ventilation requires an air velocity of 1.0 to 1.5m/s in order to keep the egress routes smoke free (3). This is in accordance with the conclusion of the results of the fire test conducted in the Zwenbergtunnel (Austria) in the winter of 1974-75 (4) and (5). However, these tests were conducted in an abandoned railway tunnel with a cross section of barely 24 m^2 that is considerably smaller than the 59 m^2 of the modern road tunnel of interest here. Therefore, the issue is revisited using CFD and egress modelling techniques.

2 INTRODUCTION

No single optimal longitudinal ventilation velocity exists, as it depends on the size and location of the fire as well as on the tunnel users. However, in a practical sense only one air velocity can be applied for the ventilation-control routines. Consequently, the criteria in order to establish the best flow velocity were defined. Applying these, one single longitudinal flow velocity was derived.

In this particular case, tunnel slopes of +4% and -4% were examined, as the slope has a large impact on the smoke-dispersion velocity. Conducting 3D CFD computations using "ANSYS CFX" at several flow velocities, the tenability in the 4.5 km long road tunnel was established. In the model-validation process, it was found that the CO-production rates reported in PIARC 99 (1) were inappropriate. Consequently, rates that are more realistic were established.

The egress modelling was conducted with an adaptation of the commercial programme "BuildingEXODUS", as otherwise unrealistic human behaviour would occur. Furthermore, two distinct egress scenarios were analysed: "ideal" and "realistic" egress. The egress modelling was fully transient and incorporated the spatial time-dependent variation of CO-concentration, temperature, radiation and visibility, which also has an impact on the individual egress speed. These tenability conditions were computed with the CFD model.

Based for the study on optimal fire ventilation at congested traffic was a tunnel that is part of a new approximately 5.6 km long dual carriageway. The tunnel consists of two tubes with unidirectional traffic. The ventilation system of the tunnel is a longitudinal-ventilation system using jet fans. An overview of the tunnel sections including cross passages, ventilation equipment (jet fans) as well as the domains chosen for CFD computations and the egress route modelling is shown in Figure 1.

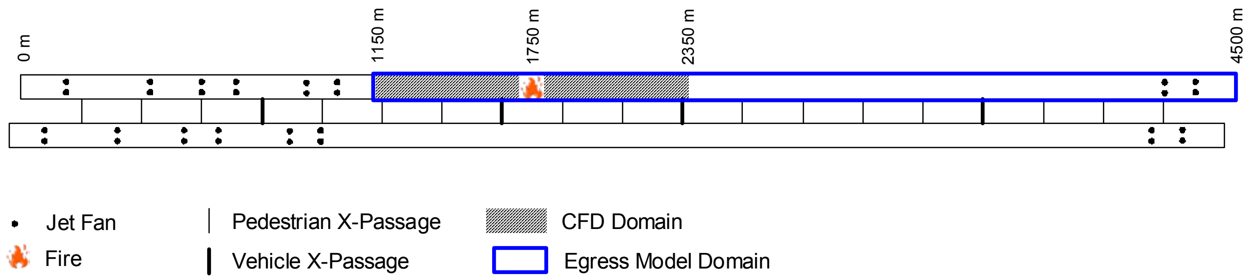

Figure 1 Schematic of the tunnel indicating the CFD and the egress model domains

3 CFD COMPUTATIONS

3.1 CFD Model and Test Cases

The study was restricted to heat-release rates below 30 MW.

Various stationary computations were carried out varying the nominal longitudinal velocity, the gradient and the heat-release rate, see Table 1. The nominal flow velocity was imposed on the inflow portal of the tunnel. All cases listed below assume congested traffic with halted vehicles on both sides of the fire. The CFD model includes vehicles in the tunnel both upstream and downstream of the fire location. All relevant data used as input for the fire modelling in the CFD computations were based on the EUREKA experiment "Public Bus" (1) and (6). However, the CO-production rate was scrutinized in more detail, see section 3.2 below.

Gradient, Heat-release rate	Nominal velocity, m/s			
	0.5	1.0	1.5	2.5
-4%, 30MW	✔	✔	✔	✔
+4%, 30MW	✔	✔	✔	✔
-4%, 5MW	x	✔ CFD only	x	x
+4%, 5MW	x	✔ CFD only	x	x

Table 1 Test-case matrix

3.2 CO-Production

The CO concentrations as calculated by the CFD model were input to the egress model. Since CO has major influence on the tunnel users, it is of the utmost importance that the values are realistic.

PIARC (1) reports CO-production rates of the EUREKA experiments (6). In spite of the advantage that the data base on large-scale experiment, it was found that the calculated CO-production rate from this experiment was inappropriately causing too high CO concentrations. The reason is probably that the EUREKA experiments were under ventilated, which is not the case here.

According to Drysdale (7), the fuel/CO-conversion factor is below 0.04 kg CO/kg fuel for well-ventilated fires i.e. an equivalence ratio << 1. The equivalence ratios for the scenarios considered with nominal velocities of 0.5 m/s to 5 m/s are in this range. For comparison, the calculated fuel/CO-conversion factor based on the EUREKA experiments is approximately 40% higher.

In (8), the "British Standard on Fire Safety Engineering, DD240: Part 1: 1997" is referenced in relation with a method for determining CO-production rates. The standard provides a fuel/CO-conversion factor of 0.013 kg CO/kg Fuel for determining the CO-production rate from a fully ventilated fire.

In order to prevent underestimating the computed CO concentrations, a fuel/CO-conversion factor of 0.04 kg CO/kg Fuel was used for the CFD computations.

The CFD model using a fuel/CO-conversion factor of 0.04 kg CO/kg Fuel predicted maximal CO concentrations adjacent to the ceiling in the order of 3500 ppm at a nominal air velocity of 0.5 m/s, 2000 ppm at a nominal air velocity of 1.5 m/s and 800 ppm at a nominal air velocity of 2.5 m/s. These values are in line with the results from the "public bus" EUREKA fire tests, in which a peak concentration of 2900 ppm was measured. The CO concentration was measured at head height at a distance of 20 m to 30 m downstream of the fire. The corresponding value predicted by the CFD model at head height with a nominal air velocity of 0.5 m/s was about 1800 ppm. Since the CO concentrations depend highly on the ventilation and on the type of the burning material, these values from the EUREKA fire test can only serve as rough estimates.

3.3 Validation

The CFD model was validated against two fire tests in the Memorial Tunnel (9):

- 615B with a heat-release rate of 100 MW and a longitudinal velocity of 2.5 m/s and
- 607 with a heat-release rate of 15 MW and a longitudinal velocity of 2.3 m/s.

Figure 2 shows good agreement between prediction and measurements of volume flow and temperatures of the Memorial Fire Test 615B.

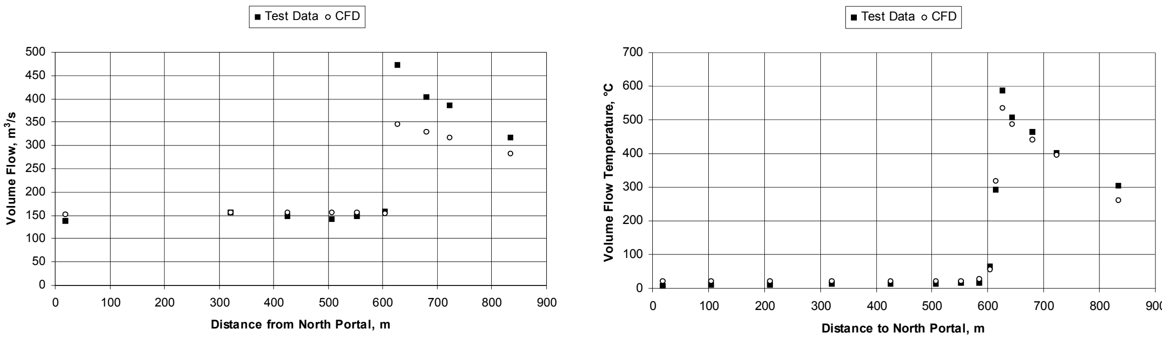

Figure 2 Volume Flow and Volume Flow Temperature in the Memorial Tunnel for test case 615B

Also in case of the Memorial Test Case 607, the predictions of temperature and velocities agrees well with the experiments. Considering that the CO measurements are believed to be very inaccurate, acceptable agreement is also obtained for the prediction of CO as seen in Figure 3.

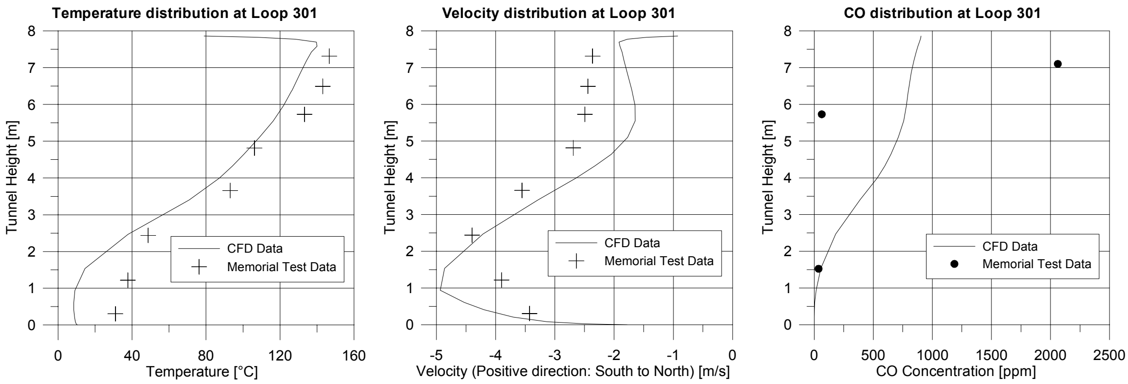

Figure 3 Comparison of CFD prediction with test data for temperature, velocity and CO concentration at Loop 301 (100 m downstream of the fire) for Memorial test case 607. Measurements of CO are considered to be inaccurate.

3.4 Results

The CFD results were prepared in view of the egress model applying zones with lengths of 18 m; see section 4.2 for details of the zones. Temperatures, CO concentrations and extinction coefficients were evaluated for heights of 1.7 m and 1.0 m above the road surface.

Two competing effects were observed. Increasing the nominal air velocity led to higher dilution of smoke and CO concentrations followed by a reduction of temperatures. Depending on the backlayering, the smoke propagation velocity can be considerably higher than the nominal air velocity. For the downhill gradient of -4 %, a 30 MW fire and a nominal velocity of 2.5 m/s, the smoke-propagation velocity was 4.3 m/s.

The distributions of the relevant values depend on the gradients. In case of the uphill gradient +4%, the values of CO and extinction at the height of 1.7 m are almost identical with those at 1.0 m; see Figure 8 and Figure 9. Figure 4 to Figure 9 summarize the results from the CFD computations for downhill and uphill gradients.

Downhill Gradient -4%, 30MW

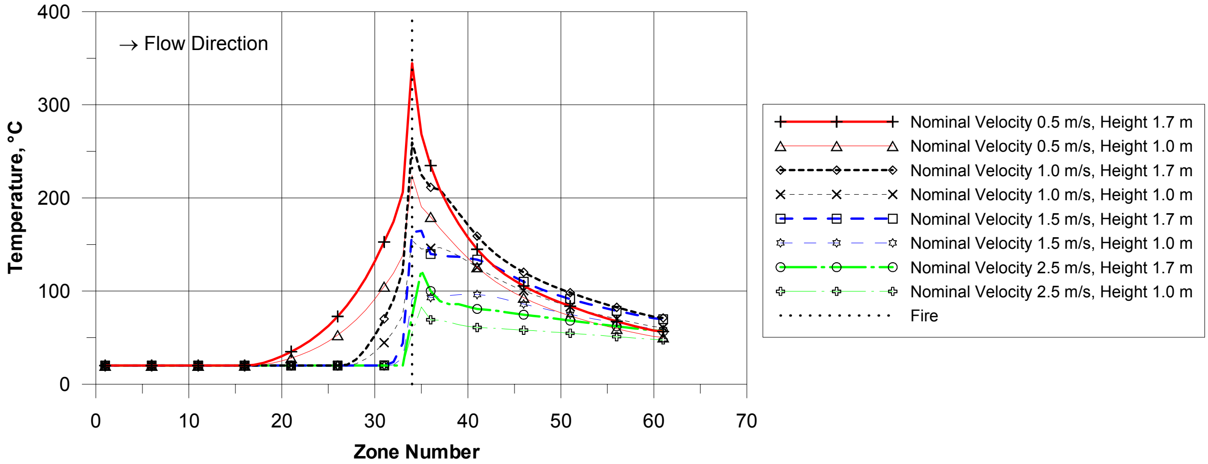

Figure 4 Temperatures at heights 1.7 m and 1.0 m in case of 30 MW fire and downhill gradient

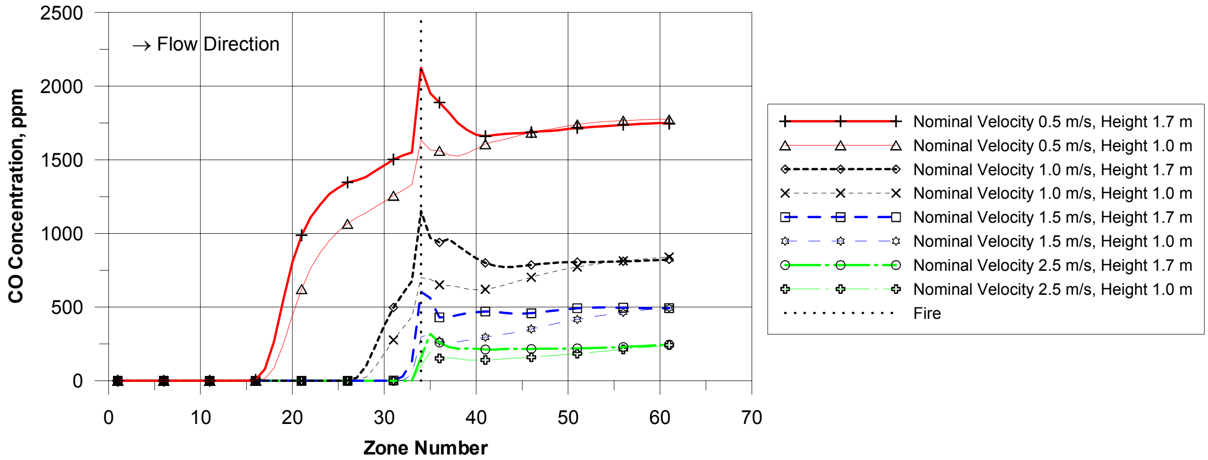

Figure 5 CO concentrations at heights 1.7 m and 1.0 m in case of 30 MW fire and downhill gradient

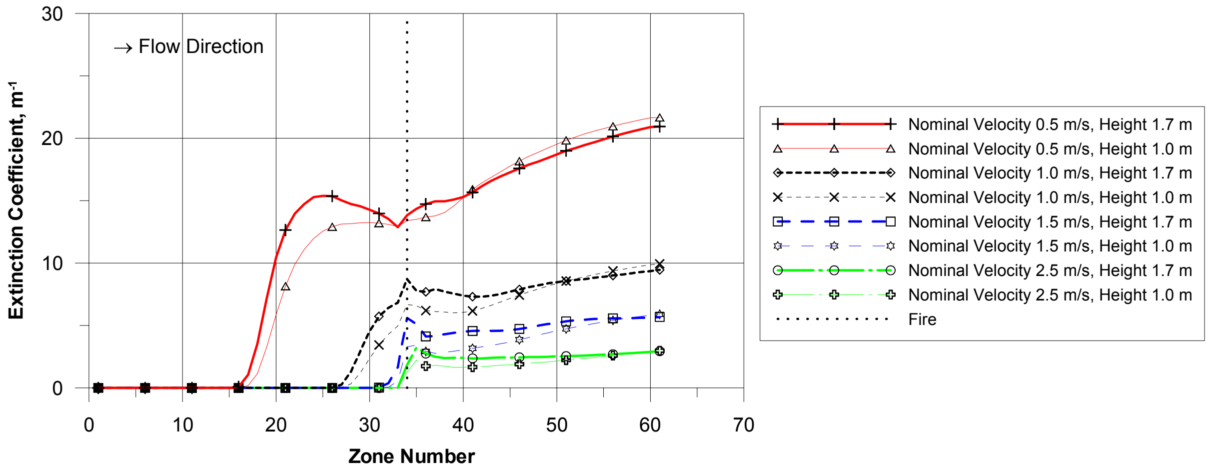

Figure 6 Extinction coefficients at heights 1.7 m and 1.0 m in case of 30 MW fire and downhill gradient

Uphill Gradient +4%, 30MW

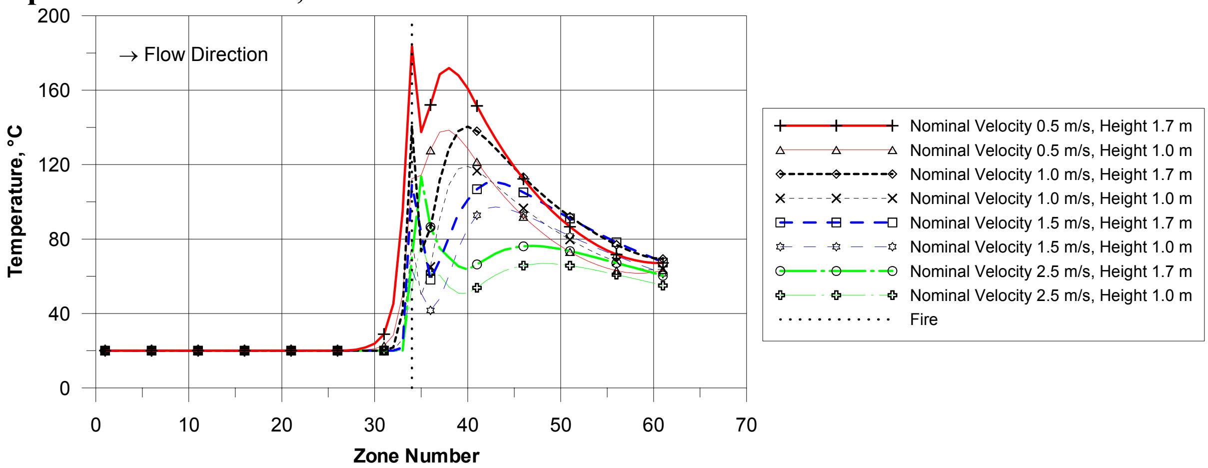

Figure 7 Temperatures at heights 1.7 m and 1.0 m in case of 30 MW fire and uphill gradient

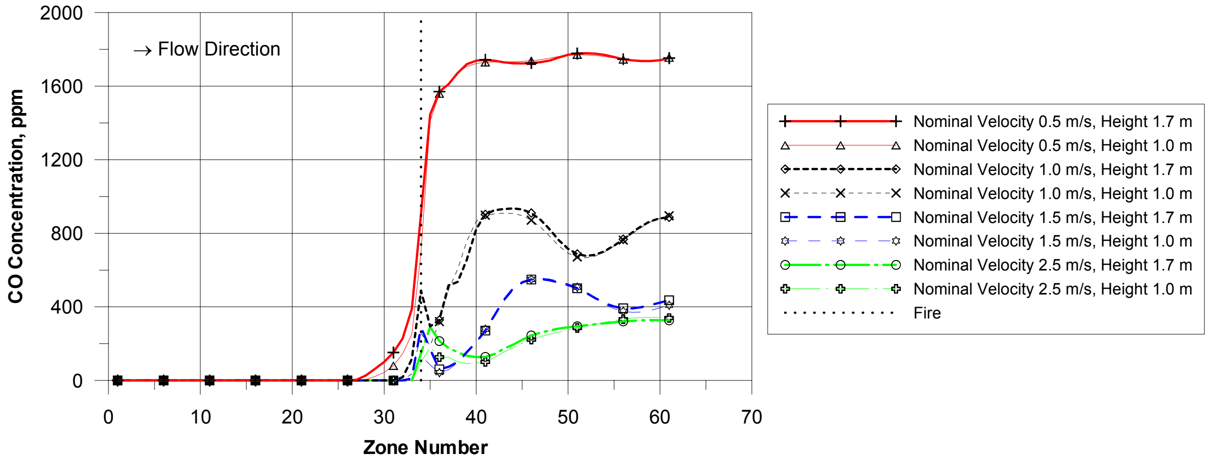

Figure 8 CO concentrations at heights 1.7 m and 1.0 m in case of 30 MW fire and uphill gradient

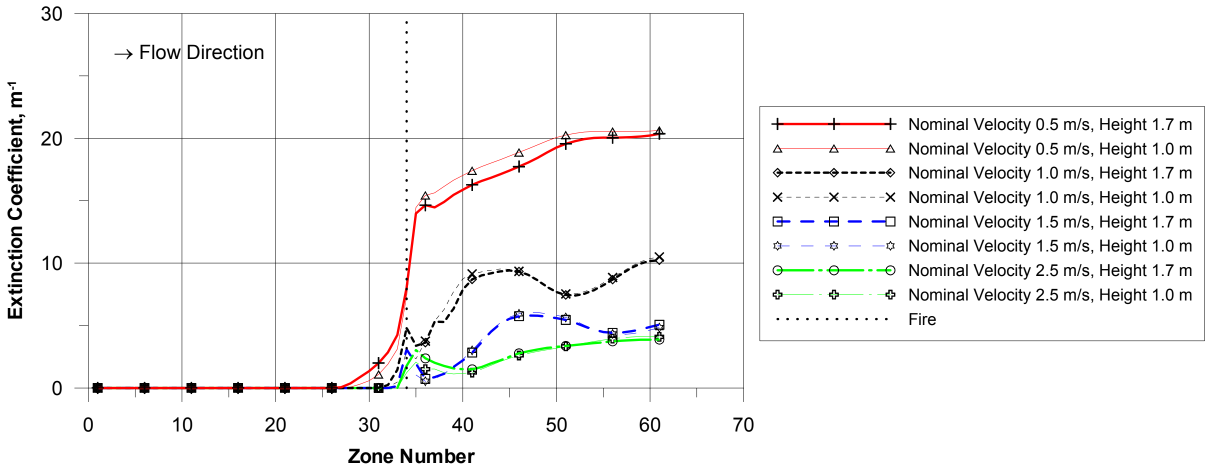

Figure 9 Extinction coefficients at heights 1.7 m and 1.0 m in case of 30 MW fire and uphill gradient

3.5 Comparison of 30 MW and 5 MW fire

The results of the study should be applicable for fires with a heat-release rate between 5 MW and 30 MW. Hence the aim of the CFD computations using 5 MW was to prove that the egress conditions are more beneficial for the 5 MW than for the 30 MW fire at the range of nominal flow velocities examined. Figure 10 compares temperatures, extinction coefficients and CO concentrations for the two heat-release rates for the downhill gradient applying a nominal flow velocity of 1 m/s. All values corresponding to the 5 MW fire are significantly lower than the ones for the 30 MW fire. Consequently, at nominal flow velocities in the vicinity of 1 m/s, the egress conditions are always more favourable for a 5 MW fire than for a 30 MW fire.

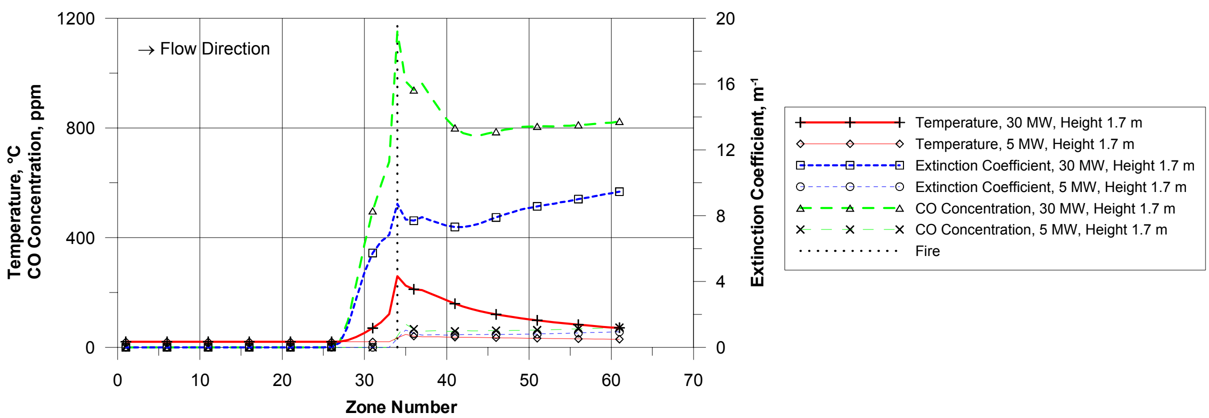

Figure 10 Comparison of 30 MW and 5 MW fires for downhill gradient -4% at a nominal flow velocity of 1 m/s.

4 EGRESS ROUTE MODELLING

4.1 Application of BuildingEXODUS

BuildingEXODUS is a zone model that simulates egress situations in case of fire by considering people-people, people-fire and people-structure interaction. A statistical model is used in order to set the attributes to the people concerned. Therefore, the results of two computations using the same input parameters vary. The effects of the tunnel air (CO and temperature) as well as visibility are taken into account. Initial computations showed that people may try to cross the location of the fire which is considered to be unrealistic. Consequently, a separation of the two sides of the fire was undertaken. Three time periods were considered: 10 min, 20 min and infinity time after the onset of the fire. Moreover, two types of egress behaviour were analysed:

- Realistic egress in which case the tunnel users are inclined to egress trough the portals
- Ideal egress in which case the tunnel users would primarily use the nearest exit.

4.2 Geometry

The egress-route modelling was carried out for congested traffic. As in the CFD model, it was assumed that the heavy-goods vehicles (HGV) are located on one lane and the passenger cars on the other, see Figure 11.

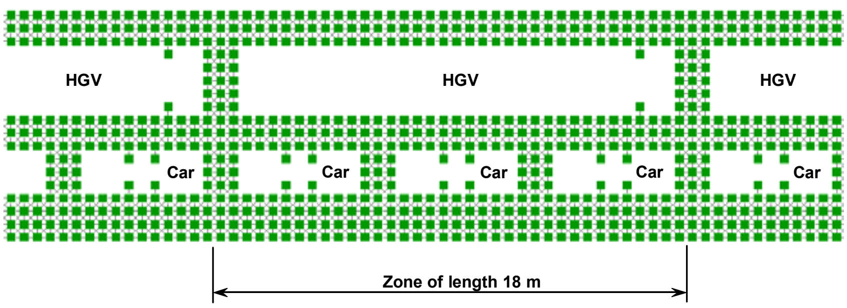

Figure 11 Modelling of HGV and passenger cars in the tunnel

Each zone had a length of 18 m and contained one HGV and three passenger cars. The length of the CFD domain is 1188 m corresponding to 66 zones. In order to model the whole part of the tunnel downstream of the fire, a total of 183 zones were defined, see Figure 12.

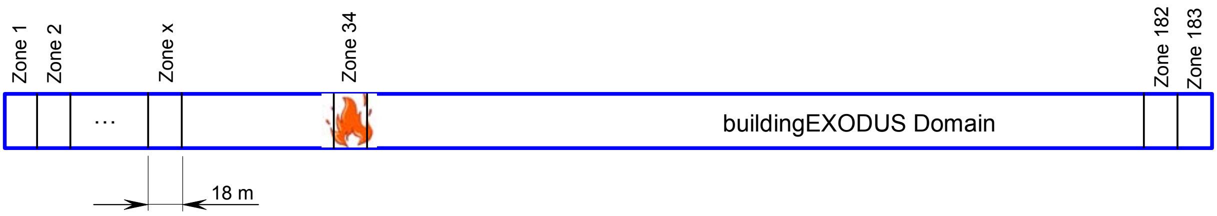

Figure 12 Zones of the CFD and buildingEXODUS domain

Based on the CFD computations, temperatures, CO concentrations and extinction coefficients were set for each zone for heights of 1.7 m and 1.0 m above the road surface. Far downstream of the fire, i.e. zones 61 to 183, the values were assumed to be constant.

The temperature, CO concentration and extinction coefficient for the zones varied with time. The smoke-propagation velocities for each side of the fire were derived from the CFD computation in order to define the conditions of the zone as a function of time.

4.3 Population (people)

A population is made up of individual occupants. Each occupant has a set of attributes that are used to define and track each individual throughout the simulation. Some of the attributes are fixed, whereas others are dynamic that changes as the simulation progresses. The attributes of HGV and car drivers, as well as car and bus passengers were randomly distributed according to certain criteria. The HGV drivers were randomly chosen from the group males from 30 to 50 years of age. No HGV passengers were supposed. The car drivers were randomly chosen from a population of males and females between 18 and 80 years of age. For the car passengers, the standard population in BuildingEXODUS was extended to including children.

In order to obtain more distinct results, the number of persons situated close to the fire was increased by adding one bus on each side of fire, as shown in Figure 13. A detailed view of the bus containing 50 people is shown in Figure 14. The total number of individuals is 1293 with an average age of 41.5 years.

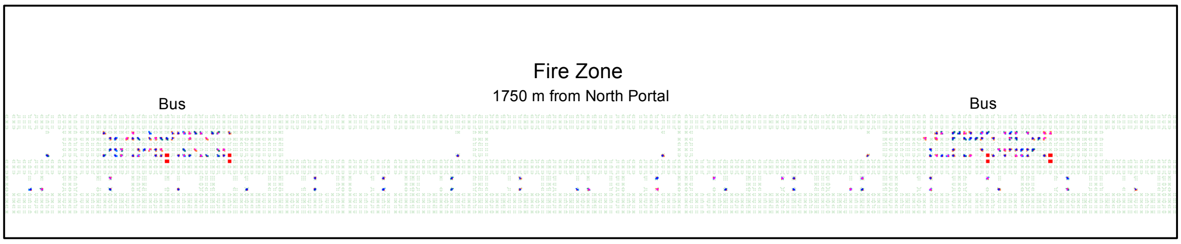

Figure 13 Vehicle configuration near the Fire Zone. Two buses are shown, each containing 50 individuals.

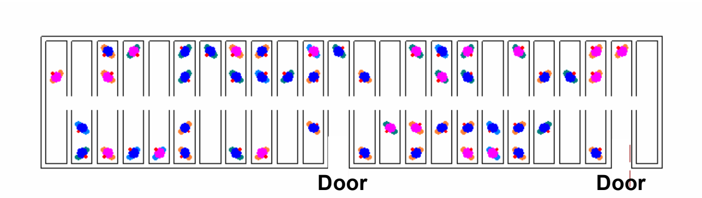

Figure 14 Modelling of a bus containing 50 people

4.4 Influence of Convective Heat, Radiative Heat, CO and Smoke on the tunnel users

The egress model includes the effect of convective heat, radiative heat, CO and smoke on the tunnel users by measuring the tunnel user's cumulative exposure. In case of CO, the exposure directly influences the egress speed, long-term health and may cause fatality.

Obscuration by smoke is represented by implementing extinction coefficients. Once caught in smoke, the tunnel user is forced to reduce the egress speed which is catered for in the model. The egress speed is reduced to 0.27 m/s when the extinction coefficient exceeds a value of 0.5 m^{-1}, which corresponds to a visibility of approximately 4.5 m. In this case, the model applies the tenability values implemented for the height of 1.0 m above the road surface (instead of 1.7 m). A post-processing picture showing the obscuration by smoke and the tunnel users escaping through an exit door is shown in Figure 15.

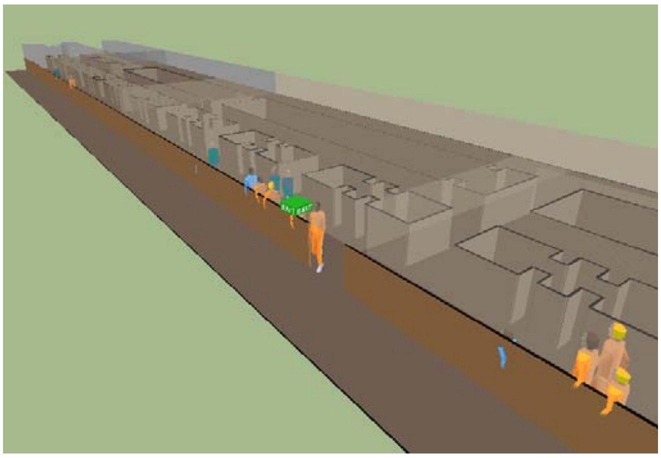

Figure 15 Obscuration by smoke. Tunnel users escaping through an exit door.

4.5 Results in Case of Realistic Egress Behaviour

In accordance with the findings in (10), the realistic egress behaviour assumes that most of the tunnel users try to escape using the tunnel portals. Only few people use the cross-passage doors.

Downhill Gradient -4%

People who successfully escaped, people caught in smoke, fatalities as well as egress times for the downhill gradient are shown in Table 2.

	t_{Sim} = 10 min			t_{Sim} = 20 min			$t_{Sim} = \infty$			
Nominal Velocity, m/s	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	Egress Time, min
0.5	889	53	0	1056	2	5	1289	0	5	37.5
1.0	918	10	0	1099	8	0	1284	0	9	37
1.5	959	95	0	1105	143	0	1196	0	97	47
2.5	982	271	0	1066	227	0	1137	0	156	64

Table 2 Table of people who successfully escaped (People out), of people caught in smoke and of fatalities in case of a downhill gradient based on realistic egress behaviour.

Within the first 10 min, about three-quarters of the people manage to reach a safe haven. The largest number of people in a safe place is achieved at the nominal air velocity of 2.5 m/s. On the other hand, at this velocity more people are caught in smoke than at lower air velocities. Also at 1.5 m/s, some people are caught in smoke. The people caught in smoke result in fatalities as the simulation time increases. The reason is the exposure to CO. At 1.0 m/s, the conditions are best since the smoke spreads in both directions at similar velocities which is a trifle lower than the average escape speed of the people. Within the first 20 min, fatalities only occur at the lowest air velocity of 0.5 m/s. The lowest egress time of about 37 min is achieved at a nominal flow velocity of 1.0 m/s.

Uphill Gradient +4%
People who successfully escaped, people caught in smoke, fatalities as well as egress times for the uphill gradient are shown in Table 3.

	t_{Sim} = 10 min			t_{Sim} = 20 min			$t_{Sim} = \infty$			
Nominal Velocity, m/s	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	Egress Time, min
0.5	923	195	0	1044	77	172	1052	0	241	25.5
1.0	936	254	0	1067	188	38	1066	0	227	31
1.5	970	294	0	1057	236	0	1114	0	179	44
2.5	965	328	0	1056	237	0	1095	0	198	50

Table 3 Table of people who successfully escaped (People out), of people caught in smoke and of fatalities in case of an uphill gradient based on realistic egress behaviour.

The number of people reaching a safe place is similar for all nominal air velocities. However, the number of people caught in smoke increases with the nominal velocity. The higher the nominal velocity the faster the people are caught by smoke and hence trapped. After 10 min, almost all people downstream of the fire, who have not yet reached a safe place, are caught in smoke. Within the first 10 min, no fatalities are recorded. But during the succeeding 10 min, at low velocities of 0.5 m/s and 1.0 m/s, fatalities are predicted as a result of high CO concentrations. In case of 1.5 m/s and 2.5 m/s, no fatalities are predicted within the first 20 min. However, as the simulation time increases, the number of fatalities rises.

4.6 Results in Case of Ideal Egress Behaviour

In case of the ideal egress behaviour, the tunnel users used the nearest exit (exit door or portal).

Downhill Gradient -4%
People who successfully escaped, people caught in smoke, fatalities as well as egress times for downhill gradient are shown in Table 4.

	t_{Sim} = 10 min			t_{Sim} = 20 min			$t_{Sim} = \infty$			
Nominal Velocity, m/s	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	Egress Time, min
0.5	1266	27	0	1293	0	0	1293	0	0	12.5
1.0	1293	0	0	1293	0	0	1293	0	0	8.5
1.5	1293	0	0	1293	0	0	1293	0	0	5
2.5	1293	0	0	1293	0	0	1293	0	0	4

Table 4 Table of people who successfully escaped (People out), of people caught in smoke and of fatalities in case of a downhill gradient based on ideal egress behaviour.

Only at 0.5 m/s are people caught in smoke within the first 10 min. At higher air velocities, all tunnel users have reached a safe place within this time. No fatalities are predicted. This is a direct consequence of the reduced exposure time as people egress using the nearest exit.

Uphill Gradient +4%
People who successfully escaped, people caught in smoke, fatalities as well as egress times for uphill gradient are shown in Table 5.

	t_{Sim} = 10 min			t_{Sim} = 20 min			t_{Sim} = ∞			
Nominal Velocity, m/s	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	People out	People caught in smoke	Fatalities	Egress Time, min
0.5	1293	0	0	1293	0	0	1293	0	0	6
1.0	1293	0	0	1293	0	0	1293	0	0	6
1.5	1293	0	0	1293	0	0	1293	0	0	5
2.5	1293	0	0	1293	0	0	1293	0	0	4

Table 5 Table of people who successfully escaped (People out), of people caught in smoke and of fatalities in case of an uphill gradient based on ideal egress behaviour.

In the case of an uphill gradient, all people managed to escape within the first 10 min.

5 DETERMINATION OF THE BEST VENTILATION STRATEGY

An increase in nominal flow velocity has mainly two effects. It enhances dilution of CO and reduces the temperatures, which are advantageous effects. On the other hand, it increases the smoke-propagation velocity which leads to more people being caught in smoke. This is certainly undesired and therefore a disadvantageous effect.

20 min after the onset of the fire is considered adequate time to allow self rescue and some assisted rescue. Therefore, the objective is to apply a nominal air velocity in order to minimize the number of casualties for this time period. Moreover, the number of people caught in smoke should be minimized, as they have limited chances of rescue. Consequently, based on the results of the egress-route modelling, which emphasises the two competing effects of the nominal flow velocity, the best ventilation strategies are determined according to the following criteria:

- Criterion 1: No fatalities within 20 min, which should allow adequate time for self rescue and assisted rescue.
- Criterion 2: Minimum number of people caught in smoke after 20 min, as such are difficult to rescue.

Criterion 1 is satisfied for nominal velocities of ≥ 1.0 m/s in case of a downhill gradient and for nominal velocities ≥ 1.5 m/s in case of an uphill gradient. Criterion 2 is satisfied for nominal velocities as low as possible for downhill and uphill gradients. Figure 16 summarises the best ventilation strategy depending on the location of the fire as well as for the case that the position of the fire is unknown.

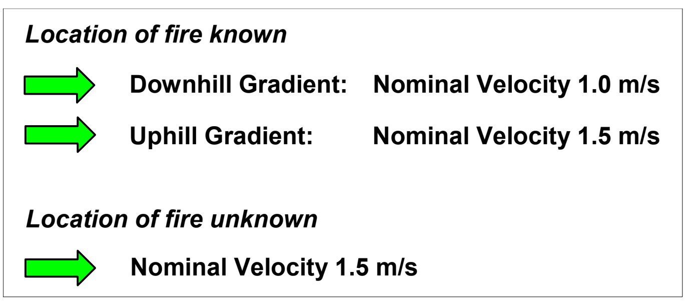

Figure 16 Best ventilation strategy for congested traffic

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