Prepared for:

The Administration of the Union Territory of Ladakh
PWD (R&B)

सत्यमेव जयते

Project:

Detailed Project Report (DPR) for preparation of various Road/Tunnel projects of Public Works (R&B) Department, UT of Ladakh - Highway tunnel across Fotu La Pass (1.7 Km approx.) along with its approaches on Zojila - Leh - Kargil Road

Subject:

FOTULA TUNNEL
TUNNEL VENTILATION DESIGN REPORT
VOLUME-2D

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Revision History

Rev.	Date	Long Description

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Executive Summary

Report contains the tunnel ventilation system (TVS) design pertaining to Detailed Project Report (DPR) of Fotu La Tunnel. The proposed tunnel is a twin tube, unidirectional, two-lane, all-weather tunnel. Ventilation system has been designed for longitudinal flow based on critical velocity criteria and back layering of smoke. 50 MW HRR load for fire has been considered as the worst-case emergency scenario. BS IV equivalent to EURO IV is the base pollution standard considered for the design. The operating power is coming out to be 3.51 MW.

1 INTRODUCTION

The proposed twin tube tunnel is located in UT of Ladakh across Fotu La pass. Its Westbound tube starts at Km 0+200 and ends at Km 2+200. Eastbound tube starts at starts at Km 0+220 and ends at Km 2+200. The approximate length of tunnel is 2.0 kilometres.

1.1 Scope of the Analysis

Table 1 and Table 2 indicate the tunnels that are covered in scope of work.

Table 1: General Details of westbound Tunnel

Tunnel	Entry Portal		Exit Portal		Length (Km)	Gradient %
	Elevation	Chainage	Elevation	Chainage		
West bound	3893.728	0+200	3870.048	2+200	2	4

Table 2: General Details of Eastbound Tunnel

Tunnel	Entry Portal (ENP)		Exit Portal (EXP)		Length (Km)	Gradient %
	Elevation	Chainage	Elevation	Chainage		
East bound	3893.9	0+220	3854.98	2+200	1.98	4

2 KEY INPUT DATA (DESIGN BASIS)

This section summarises the inputs that are important for simulations. These inputs are associated with environmental conditions, geometric aspect of the tunnel, thermal aspects of the tunnel and fire HRR.

Table 3: Typical Input Parameters

S. No.	Description	Value
1.	Length of the Tunnel	2.00 km
2.	Cross sectional area of the Tunnel	70.16 m^2
3.	Hydraulic Diameter of Main Tunnel	8.90 m
4.	Cross sectional area of the Cross-passage doors	18.2 m^2
5.	Hydraulic Diameter of Cross-passage doors	4.2 m
6	Length of Cross-Passages	13.70 m
7	Ambient Temperature	19.9 ^oC (Annual Cooling 1 % Design Conditions)
8	Tunnel Wall Temperature	-3.5 ^oC
9	Adverse pressure acting on the portal	250 Pa
10	Tunnel friction factor, λ	0.02
11	Fire Heat release rate	50 MW
12	Vehicle Drag coefficient	0.4 (PC, LDV), 0.8 (HGV)
13	Speed limit in Tunnel	80 km/hour
14	Vehicular Speed during Congestion	10 km/hour
15	Emission Standard	EURO IV/BS IV

3 DESIGN CRITERIA

Vehicles on the open road create emissions which are diluted and dispersed through natural surface air flows. Road tunnels create an enclosed space around vehicles where emissions from the vehicles can build up to unacceptable levels without an engineered ventilation system to replace natural surface air flows. The basic principle of tunnel ventilation is dilution of vehicle emissions by providing fresh air and then removing the exhaust air from the tunnels. The exhaust air can be removed via a portal (a location where the tunnel carriageway opens to the surrounding environment), via a ventilation outlet (such as a stack), or via a combination of both. This objective can be achieved by the following:

- Preventing the dangerous accumulation of vehicle-emitted pollutants (i.e., carbon monoxide CO, and oxides of nitrogen, NOx)
- Maintaining visibility in the tunnel by preventing the accumulation of haze-producing pollutants.

During normal tunnel operations, the tunnel length, the traffic density, and the direction of traffic movement are some of the key factors in determining whether the ventilation requirements can be achieved by passive means (e.g., the piston action airflow generated by the moving vehicle) or whether mechanical ventilation is required.

In addition to vehicle emission, the assessment of fire safety in tunnels is also a complex issue. For fire safety in tunnels, multi-disciplinary criteria shall be explored for identifying the causes and development of fire. Based on the analysis, evaluation measures shall be identified to prevent and reduce the consequences of fire. The priority for fire design of all tunnels is to ensure:

- Prevention of critical events that may endanger human life, the environment, and the tunnel structure & installations.
- Self-rescue of people presents in the tunnel at the time of fire.
- Limitation of the material and structural damage.

The tunnel length is also a key factor in determining the need for mechanical ventilation during emergency operations, since it effects the egress time from the tunnel and the number of motorists that could be exposed to the hazards of a fire.

3.1 Purpose of the Tunnel Ventilation System

The tunnel ventilation is required to ensure that the tunnel will operate with low risk and with acceptable air quality at all times. The operating conditions can be divided into the following categories.

- Normal Operation – Traffic is freely flowing.
- Congested Operation – Traffic is slow moving due to vehicle build up.
- Emergency Operation – These are operations that require the intervention of emergency

services.

In general, the tunnel ventilation system has the following purposes:

- Monitoring and controlling of air quality (pollutants and visibility) inside the tunnel to meet the design requirements for tunnel user under normal, and congested operations by using both longitudinal as well point extraction system.
- Prevention of smoke back-layering and smoke spreading upstream and downstream of the incident vehicle (emergency operations) again by using point extraction as well longitudinal system.3.2 Modelling Methodology

Detailed Modelling of ventilation system was carried out using IDA Road Tunnel Software. The ***Chapter 5*** of **IRC: SP:91-2019** provides guidance on the length, shape, size, tunnel environment and complexion of the likely traffic for which tunnel has been designed. Keeping in view the models for design benchmarking were made in the software.

Here complete modelling of the systems as per the philosophy of design and operations shall be done as depicted in Figure 1.

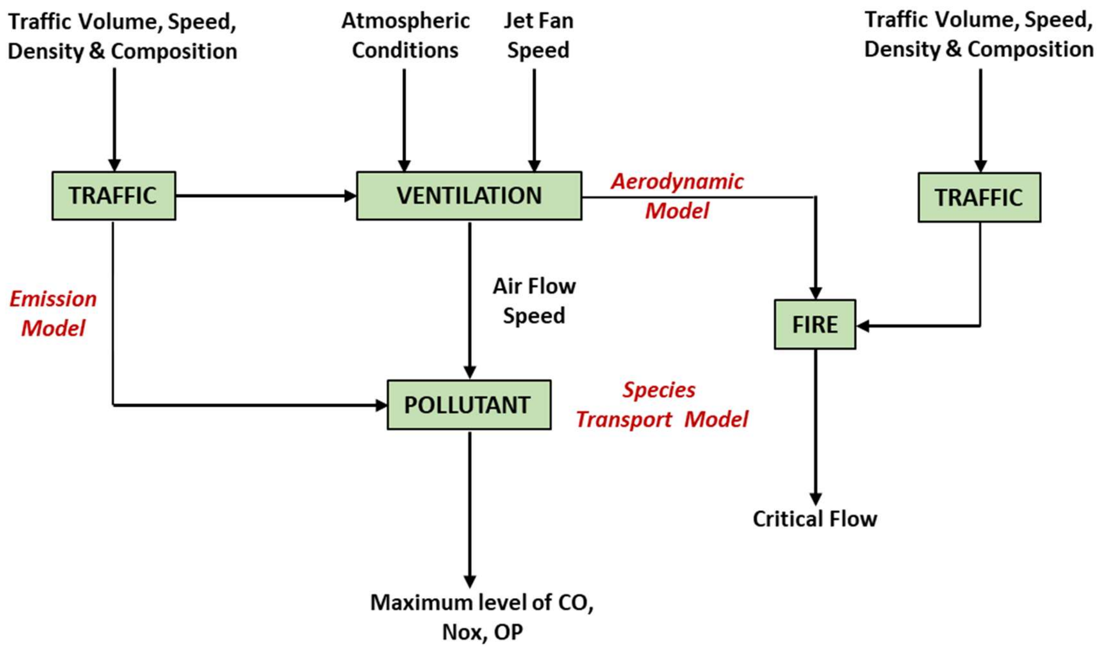


Figure 1: Design Flow Chart

3.2 Tunnel Gradient

Slope or gradient of the tunnel significantly affect the air flow movement inside tunnel. Gradient of tunnel become more important while solving critical flow requirement inside tunnel during fire incidents.

Fotu La tunnel has varying gradient. Based on the alignment drawing [17], following is the gradient for Fotu La tunnel.

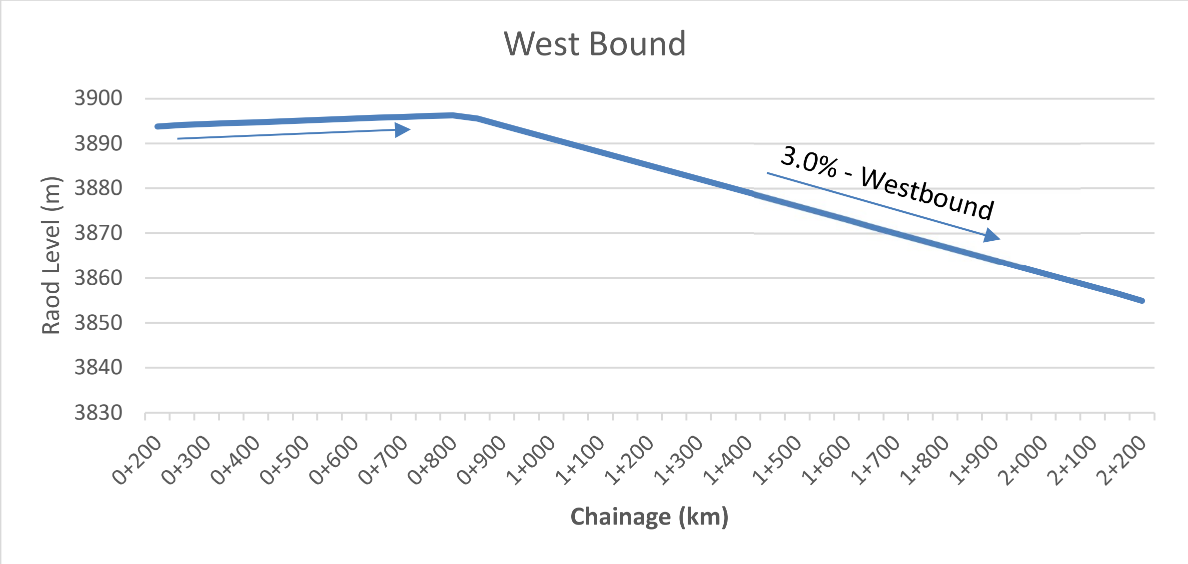


Figure 2: Gradient of Fotu La Tunnel

3.3 Tunnel Cross-sections

Following figures depicts the different cross-sectional layout for different tunnel areas [17].

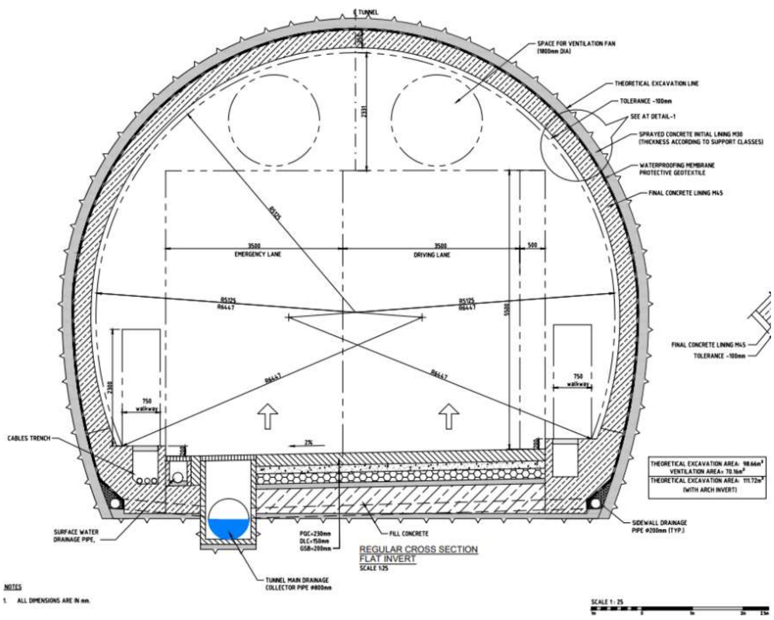


Figure 3: Cross section of main tunnel.

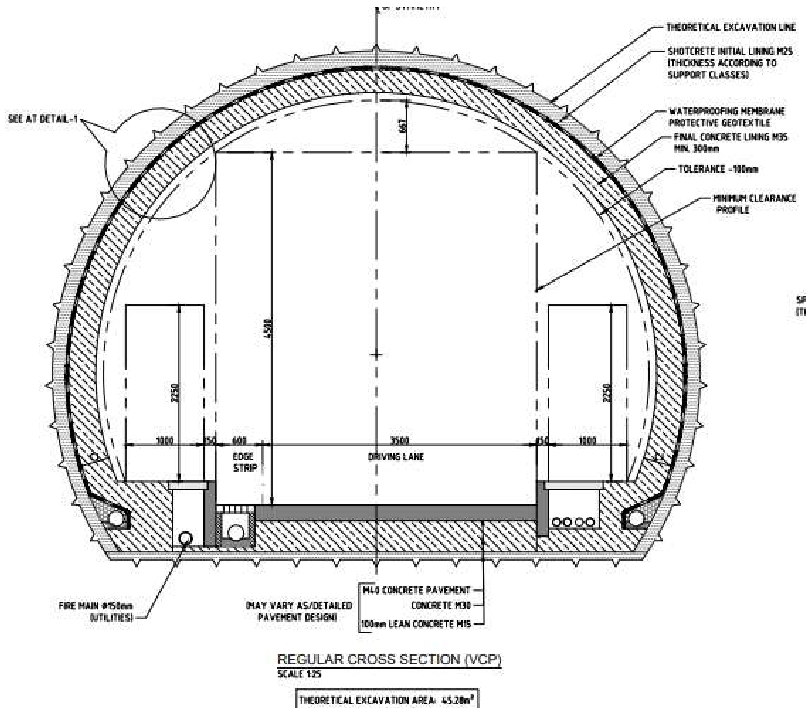


Figure 4: Cross-section of cross passage.

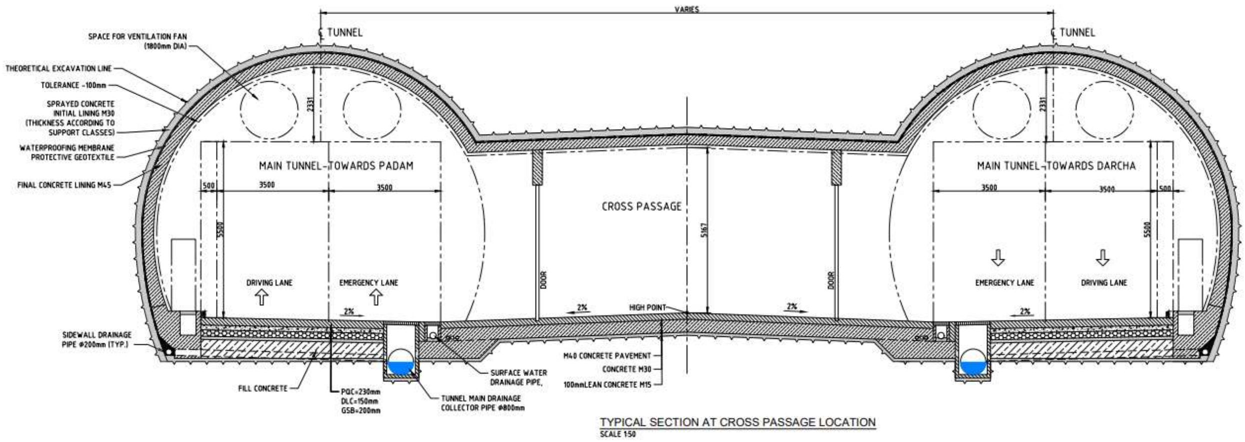


Figure 5: Longitudinal section of cross passage.

3.4 Meteorological Data

3.4.1 Ambient temperature

The design ambient condition was considered from weather data file of Leh. 1% cooling condition was considered for design.

3.4.2 Tunnel Friction Factor

Friction factor for tunnel wall has been calculated by numerical solution of Colebrook's equation considering an absolute roughness of 3 mm for concrete (based on Moody's) [14].

$$\frac{1}{\sqrt{f}} = -2 \times \log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}\right)$$

Based on the numeric calculation, a value of **0.02** has been considered for friction factor.

3.4.3 Tunnel Wall Temperature

Tunnel wall temperature was estimated based on the Ground Temperature Profile in Leh Weather conditions [18]. Tunnel wall temperature is used for predicting the upstream and downstream air temperature for fire scenario as well as buoyancy driven airflow inside the tunnel. Following figure provides the ground temperature at different soil depths. Based on the above figure, it can be assessed that average ground temperature varies between ~-9.5 to 3.0ºC through the year. Therefore, an average value of **-3.25 ºC** has been considered as tunnel wall temperature.

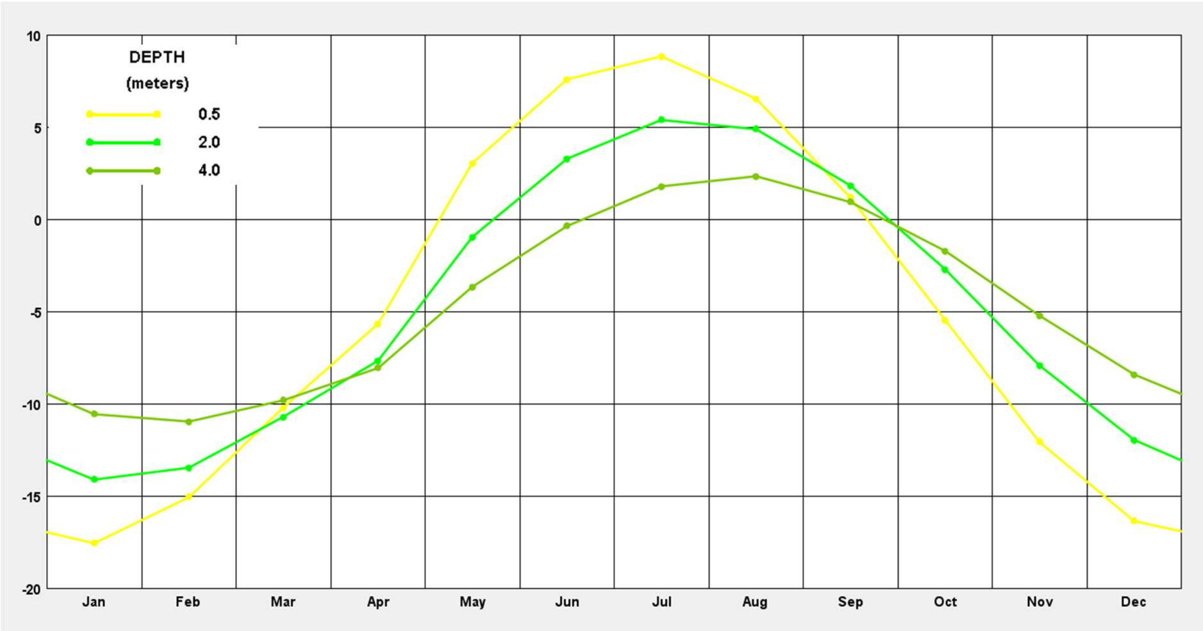


Figure 6: Annual variation of soil temperatures at different depths.

3.5 Vehicular Drag Coefficient

The vehicular drag coefficient has been assumed from Swiss Tunnel Ventilation Design Code [9]. This code has been referred due to uncertainty in Indian standards for drag coefficients.

Table 4: Vehicular drag coefficients

Vehicle Type	**Frontal Area (m^2)**	**Drag Coefficient, C_D**
Passenger Vehicles/LDV	2.73	0.4
Heavy Commercial Vehicle	6.5	0.80

3.6 Emergency Conditions

From a fire and life safety design point of view, the heat release rate in the tunnel plays an important role in tunnel to the ventilation requirements. An inappropriate selection of a design fire could result in a system that is insufficient to cater to the required tenability.

The type of vehicles, number of vehicles and the type of goods carried by these vehicles can vary considerably resulting in different heat release rate output. Vehicles on the road can vary from motorcycles to heavy goods vehicles or even a fuel tanker. In the event of a tunnel fire, the magnitude of their heat release rate can be quite different. It is also feasible that in an extreme fire scenario where up to several tens or hundreds of vehicles could be involved in a severe collision resulting in a catastrophic incident. For design applications, the choice of a design fire often corresponds to the traffic flow expected for a tunnel. This is because the material which burns in a road tunnel mostly comes from vehicles involved.

Recommendations from various guidelines such as NFPA 502, BD 78/99 and PIARC technical committee report are often used as a basis in incorporating the expected traffic flow of a tunnel to determine the design fire. Following table shows Heat Release Rate (HRR) of different type of vehicles as per different guidelines.

Table 5: Fire HRR from different guidelines

Guidelines	**NFPA 502**	**BD 78/79**	**PIARC**
	Heat Release Rate (MW)	Heat Release Rate (MW)	Heat Release Rate (MW)
Passenger Car	5 - 10	5	5-10
Light Duty Vehicle	10 - 20	15	15
Coach, Bus	20 -30	20	20
Lorry, Heavy Goods Vehicles	70 - 200	30-100	**30-50**

Based on the traffic data [16], **50 MW** Heat Release Rate (HRR) fire is considered as design value for the smoke control situation. This figure shall be appropriate assumption and shall be modelled to ascertain the compliance to the NFPA 502 environmental tenability and effectiveness of TVS design. The fan system sizing shall be based on its capability to avoid back layering of smoke by providing enough velocities in the sections so that the critical velocities criteria is met. Further temperature and visibility in the evacuation path must also be maintained as per the NFPA 502 tenability requirements. In each of these scenarios a fire size, growth rate and location shall be identified according to the NFPA 92 and in consultation with the stake holder. These fire studies vary a lot based on assumption of heat release rates. Therefore, it is important to classify fire growth assumption as to how the fire considered is representative of the situations. t-squared fire formulation (Source NFPA 92) is considered most appropriate for the project. Some of the extract of NPFA 92 are depicted below showing the fire growth and nomenclature used.

Table 6: Fire growth rate

Class	Time to Reach 1000 Btu/sec
Ultra-fast	75 sec
Fast	150 sec
Medium	300 sec
Slow	600 sec

The general equation is:

$$q = at^2$$

where:

q = rate of heat release (normally in Btu/sec or kW)
a = a constant governing the speed of growth
t = time (normally in sec)

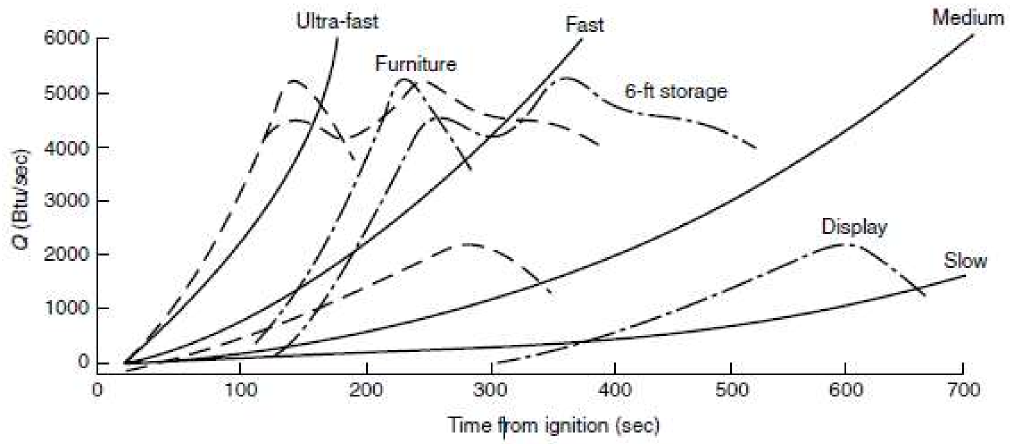


Figure 7: Fire curve with some common materials (Source NFPA 92)

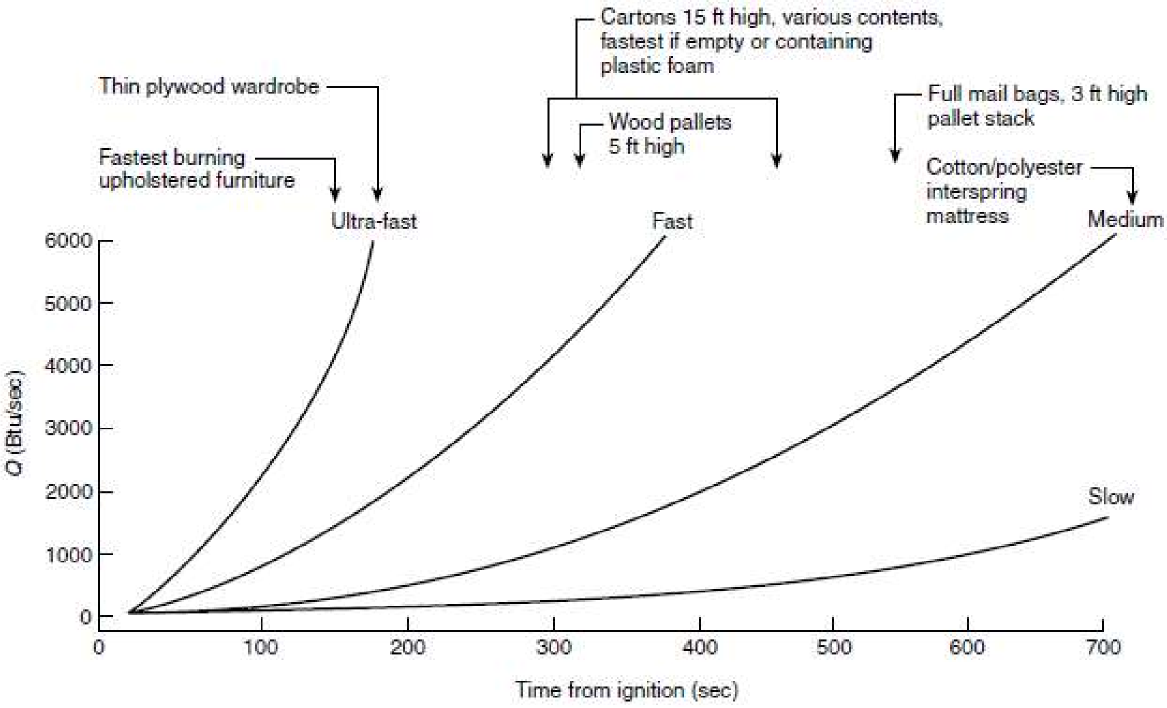


Figure 8: Fire curves hypothesis (Source NFPA 92)

Based on the above assumptions, following design fire curve was considered for the present analysis.

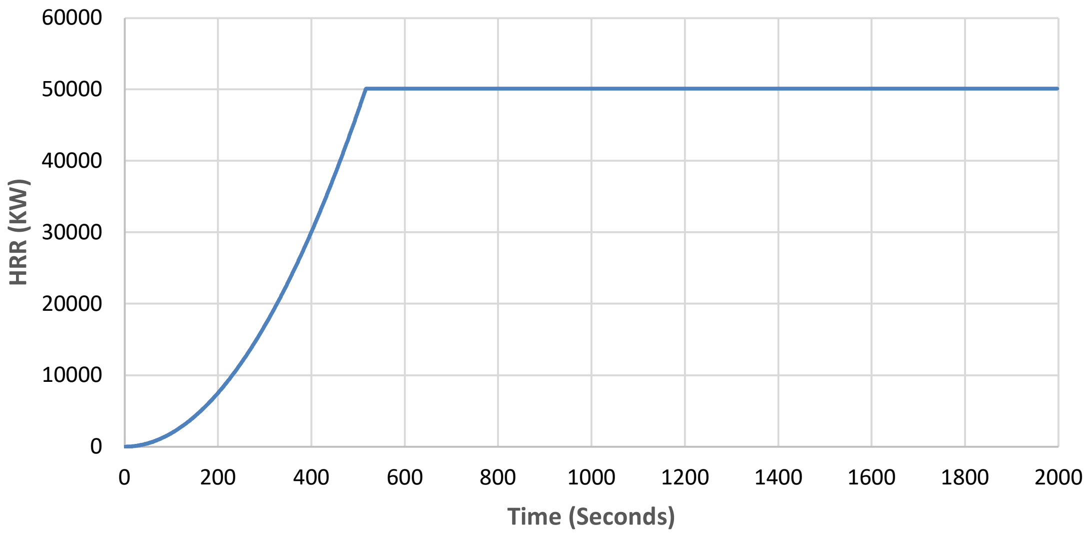


Figure 9: Design curve for 50 MW ultra-fast fire.

3.7 Traffic Density

Traffic density inside the tunnel affect the air flow movement inside the tunnel by virtue of their movement. Piston effect generated by traffic significantly affects the ventilation requirement for pollution/smoke removal. Based on the traffic report and projection [16], traffic mix was analysed. Traffic composition and category, along with other factors, also affect the pollutant generation. The traffic composition into primary (cars, light duty vehicles, heavy goods vehicles) and sub-category (gasoline and petrol) is shown in Table 7.

Table 7: Projected traffic data for year 2053

Vehicle type	10% peak factor	West Bound	East Bound
PC-D	1179	590	590
PC-G	1179	590	590
LCV-D	76	38	38
LCV-G	20	10	10
HGV	60	30	30

3.8 Air quality limits

Below table shows the air quality limits for tunnel ventilation design in case of normal and congestion operation mode as per IRC: SP:91-2019.

Table 8: Design and threshold values for pollutants as per IRC: SP:91-2019

Pollutant	Maximum permissible concentrations	Reference
CO	100 ppm (5 min average)	[1]
NO_2	1 ppm (15 min average)	[1]
Ratio of NO_2/NOx	10% by volume	[1]
Extinction coefficient (Visibility)	0.007 m^{-1}	[1]
Maximum Allowable velocity	10 m/s	[1]

3.9 Emission Standard

The pollutant emission rates from each vehicle's exhaust are dependent on:

- Type of vehicle (petrol/diesel)
- Age of vehicle
- Road gradient
- Speed of vehicle
- Altitude of tunnel

As per the Auto Fuel Policy 2025, it was mentioned to implement the BS IV norms across the country by April 2017, BS V emission norms in 2021 and BS VI norms in 2024. The percentage share of BS IV vehicles sold in domestic market was 12.3% for HCV, 24.3% for LCV and 23.0% for Passenger cars (as per Report of the Expert Committee on Auto Fuel Vision & Policy 2015). BS III was implemented in April 2010 for whole India.

Considering the above statistics and average life of LCV (~15 years) and HCV (~13 years) in India (FICCI note for replacement policy for diesel commercial vehicles; May 2015, Analysis of End of Vehicles: ELVs Sector in India), it was assumed that most of the traffic plying on the proposed route would comprise a significant portion of BS IV vehicles at the start of the project.

Therefore, design shall be based on the base year emission standards as per EURO 4 emission norms which are equivalent to BS IV emission standard.

5 DESIGN CONCEPTS FOR TVS SYSTEM

Tunnel safety is a concern in normal operating conditions as well as in emergency conditions (i.e., in case of fire). In both cases the ventilation system plays a fundamental role. In normal operating conditions it must keep air quality within acceptable safety limits. In emergency conditions, its role is to control or extract smoke to allow fast and safe smoke free evacuation and safe fire-fighting activities.

5.1 Tunnel Ventilation Systems (TVS)

The ventilation system installed in a tunnel must ensure a safe environment under both emergency and normal conditions. Smoke movement should be controlled in a fire incident. The design of ventilation systems for road tunnels depends on various parameters, such as the expected design fire and desired smoke clear height. Under normal conditions, the tunnel ventilation system design aims to prevent accumulation of vehicular emissions to dangerous levels. For dilution ventilation, fresh air entering the tunnel would mix with vehicle emissions. The polluted air will be exhausted consequently by the tunnel ventilation system. The volume of fresh air required traffic density and tunnel length are the design parameters in normal conditions. Mechanical ventilation systems commonly installed for road tunnels are longitudinal, semi-transverse, transverse, and partial transverse ventilation systems. Here, longitudinal system will be used to strategize the ventilation requirements in the tunnel.

5.2 Longitudinal Ventilation

A longitudinal ventilation system is designed to push smoke from the fire site to the exit portal in case of fire. This longitudinal concept is very effective for unidirectional traffic. People and cars downstream of the fire are assumed to have sufficient time to leave the site and would not be trapped inside the tunnel. This must be supported by good fire safety management. Installing a linear heat detection system as a monitoring device might help to locate positions with abnormal temperature rise. Furthermore, providing cross-passages between the tunnels would minimize the possibility of trapping passengers in smoke.

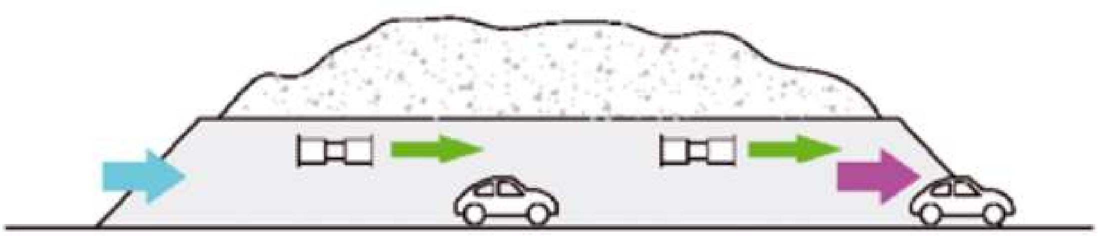


Figure 10: Longitudinal Ventilation

5.3 Critical Velocity and Jet Fan Sizes

Longitudinal ventilation is achieved by using jet fans or booster fans that, through an exchange of momentum between jet fans and mass of air in the tunnel inducing a large fresh air flow into the tunnel. During fire situations they avoid smoke back layering and keep under control the smoke propagation maintaining clear zones occupied by users. It also avoids smoke back layering which is quantified in terms of critical velocity.

The “critical velocity” is the minimum air velocity required to suppress the smoke spreading against the longitudinal ventilation flow during tunnel fire situations. The current techniques for prediction of the values of the critical velocity for various tunnels were mainly based on semi-empirical equations obtained from the Froude number preservation combining with some experimental data. The critical velocity is determined from the following coupled equations [6]:

Equation 1: Critical Velocity

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{1/3}$$

Equation 2: Hot gas temperature

$$T_f = \frac{Q}{\rho C_p A V_c} + T$$

Where,

V_C = critical velocity [m/sec]

K_1=Froude number factor, $Fr^{-1/3}$

K_g = grade factor

g = acceleration caused by gravity [m/sec^2]

H = height of tunnel at the fire site [m]

Q = heat fire is adding directly to air at the fire site [kW]

ρ = average density of the approach (upstream) air [kg/m^3]

C_p = specific heat of air [kJ/kg K]

A = area perpendicular to the flow [m^2]

T_f = *average temperature of the fire site gases* [K]

T= temperature of the approach air [K]

Jet fans are sized based on the requirement of critical velocity in tunnel. The required thrust of jet fan depends on the losses occurring during airflow in tunnel. Thrust losses depends on friction in tunnel, piston effect, gradients, and other factors such as temperature difference on portals and outside wind conditions. Arrays of Jet fans shall be installed at a considerable distance from each other. The efficiency of the jet fans can be significantly reduced if they are located too closely apart in the longitudinal direction, since a certain spacing is required to develop the velocity profile in the tunnel. There are various guidelines for minimum longitudinal distance between jet fans. Some of these refers to a minimum distance of 80 – 100 m, other reference specifies a hundred times the jet fan diameter. In either way, care shall be taken that the jet can develop freely and is not impaired by physical obstacles.

A simple theoretical model for sizing of jet fan can be expressed as follows. This model is based on the general flow theories for one-dimensional turbulent duct flow (Bernoulli's law).

Equation 3: Pressure equilibrium inside tunnel

$$\Delta p_{fan} \pm \Delta p_w \pm \Delta p_T = \Delta p_{in} + \Delta p_e + \Delta p_{fr} + \Delta p_{HGV} + \Delta p_{ob}$$

Where,

Δp_{fan} - Pressure change created by the fan (Pa)

Δp_w - Wind pressure difference between the portals (Pa)

Δp_T - Pressure difference due to density variation created by fire (Pa)

$\Delta p_{in/e}$ - Pressure loss at inlet and outlet of tunnel (Pa)

Δp_{fr} - Pressure loss due to wall friction (Pa)

Δp_{HGV} - Pressure loss due to HGV (Pa)

Δp_{ob} - Pressure loss due to other flow obstructions (Pa)

6 IDA TUNNEL SIMULATION METHODOLOGY

IDA Tunnel is a comprehensive Road and Rail Tunnel Ventilation & Fire Simulation Software, used by leading tunnel design companies, such as HBI Haerter, Gruner, Halcrow, WSP, Norconsult, Ramböll, Pöyry, and Sweco.

IDA Tunnel allows the user to simulate road and rail tunnel design projects, including full range of ventilation and fire design tasks. User will be able to get computed results that can be animated in the context of a full 3D representation of the tunnel network as shown in the image below.

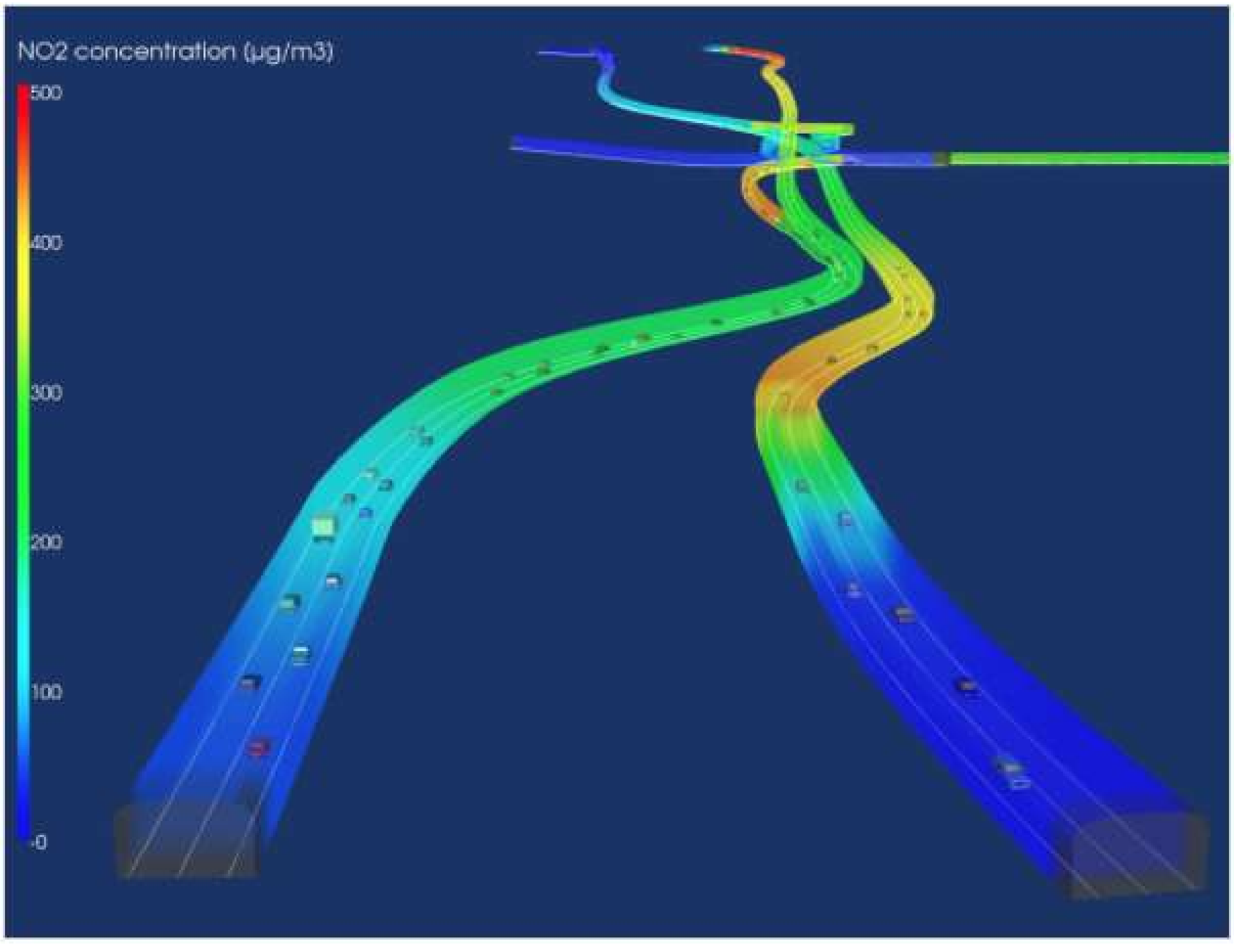


Figure 11. IDA Road Tunnel (Representation Diagram)

IDA Tunnel addresses the main climate and safety issues in road tunnel systems (except pressure transient discomfort, since its solver is of incompressible nature), and it relies on a graphical user interface for definition of the tunnel model. A schematic representation of computational components, such as tunnel sections, branches, fans, etc. are accompanied by a 3D view, where computed results and moving trains can be animated in the context of a full 3D representation of the tunnel network.

IDA Tunnel permits long-term studies using measured climatic data, including moisture, and complex schedules. Traffic movement under normal traffic and emergency conditions are simulated, based on user-supplied acceleration, retardation, and maximum power and speed parameters. Stochastic traffic patterns may be described to avoid artificial traffic synchronization effects.

1D (one-dimensional) air movement driven by traffic piston effect, buoyancy (stack effect) and wind pressure are modelled as well as air moisture with wall evaporation and condensation. The following additional air properties are also computed:

- Age, i.e., total time spent underground.
- Carbon dioxide- mostly generate by occupants.
- Particle concentration, e.g., PM10 as generated by train movements.
- Optical extinction coefficient of fire and diesel smoke.
- CO, NOx and HC, as generated by diesel engines.

7 VENTILATION EQUIPMENT – FOTU LA TUNNEL

During emergency operation, the jet fans shall operate to maintain the minimum velocity requirement at the fire zone. Jet fans shall operate to provide the required thrust for air flow towards the fire for prevention of smoke back layering. Table shows the jet fan data used for the design.

Table 9: Jet fan data: Fotu la Tunnel

Parameter	**Jet Fan Specification**	**Unit**
Outer Diameter	1570	m
Inlet Diameter	1120	m
Jet Fan Type	Reversible jet fan with silencer	-
Time for reversal (NFPA 502)	90	Sec
Stand-Thrust	2241	N
Installation Factor	0.75	%
Discharge Velocity	44.7	m/s
Motor Rating	75	kW

7.1 Number and location of Jet Fans

Based on the analysis, following number of jet fans shall be required for Fotu La tunnel. Table 10 indicates the jet fan's location in term of Chainage for respective tunnel.

Table 10: Number and Location of Jet Fans

Jet fan Bank	**Number of Jet Fan**	**Location for West Bound**	**Location for East Bound**
1	2 Jet Fan	300	300
2	2 Jet Fan	400	400
3	2 Jet Fan	500	500
4	2 Jet Fan	600	600
5	2 Jet Fan	700	750
6	2 Jet Fan	800	850
7	2 Jet Fan	900	950
8	2 Jet Fan	1400	1400
9	2 Jet Fan	1500	1500

10	2 Jet Fan	1600	1600
11	2 Jet Fan	1700	-----
12	2 Jet Fan	1800	1800
13	2 Jet Fan	1900	1900
14	2 Jet Fan	2000	2000
15	2 Jet Fan	2100	2100
Note: Each tube is to be provided with a redundant bank at CH:1050.			

8 Normal Operation

8.1 Ventilation concept in normal operation

The main objectives during normal operation are:

1. Maintain a minimum air quality along the tunnel to maintain the pollution level under the specified limit.
2. If the thrust of the traffic is sufficient to achieve the requested airflow, the jet fans are switched off.
3. Fresh air is brought into the tunnel by means of piston effect of moving vehicles.

8.2 Natural Ventilation

During period of low traffic, the ventilation shall be in specified modes. All jet fans are switched off. The airflow velocity depends on the traffic, buoyancy effects and meteorological pressure. The thrust of the moving vehicles shall lead to airflow in tunnel. Therefore, majority of the time there shall be no use of ventilation equipment. This will save significant operating cost.

9 CONGESTION OPERATION

During congestion operation, when the traffic shall be moving at minimum speed, more amount of fresh air shall be required to maintain the required pollutant level inside tunnel. Due to congestion in tunnel, vehicle density inside the tunnel increases to a threshold value. Maximum traffic at minimum speed leads to very low air velocity inside tunnel due to minimized piston effect.

10 EMERGENCY OPERATION

10.1 Ventilation concept in emergency operation

The design of the tunnel ventilation system for smoke management follows the below objectives:

1. The Purpose of longitudinal ventilation is to provide minimum amount of air flow so that critical velocity can be maintained upstream of fire location.
2. Different operation modes were simulated for emergency scenario. Each emergency mode represents fire at a particular fire zone. Different combination of jet fans was operated in supply mode (towards the fire location) and exhaust mode (away from the fire location) to prevent the smoke back-layering inside tunnel.
3. Jet fans were operated in push-pull mode to prevent the smoke back layering in the evacuation path.
4. Evacuation of people shall be in the upstream flow direction i.e., opposite of smoke movement.

11 CONCLUSION

The simulation has been performed for normal (free flowing traffic), congestion (slow moving traffic) and emergency (fire incident) scenarios based on the simulation results, following design outcomes were obtained:

1. Jet fan having minimum nominal thrust of 2241 N to be considered for ventilation system in both tubes.
2. Both West Bound and East Bound tubes require 30 and 28 jet fans respectively.
3. Both tubes shall be provided with 2 redundant banks to comply with NFPA 502 redundancy requirements.
4. A total of 58+4 jet fan of 2241 N to be required to achieve desired ventilation design criteria in the tunnel.
5. Report provides the tentative location of jet fans in Section 7.1 in terms of chainage for the tunnel.
6. Performance of ventilation system for normal operation was analysed using simulation and it was observed that pollutant concentration (CO, NOx, Opacity) is within the threshold criteria using required number of jet fans.
7. Multiple fire emergency simulation cases were performed in each tunnel to ascertain that critical velocity must be achieved during fire. Report provides the modes of operations jet fans for different fire locations in each tunnel based on the simulation results. It was observed that critical velocity requirement was met for all fire scenarios.
8. It was found that considering an adverse barometric pressure of 250 Pa the current jet fan locations and the system thrust is working out to be functionals for both fire as well as pollution scenarios.
9. The design can withstand only up to 250 Pa of barometric pressure. Any variation beyond 250 Pa may lead to a degraded and dysfunctional system. Therefore, provisions are required to establish correct barometric pressure from annual hourly portal barometric pressure differential devices.
10. The electrical load for tunnel ventilation system shall be 1.3 times of 2.7 MW operating load subjected to actual annual average barometric pressure measurement of on site. Therefore, the electrical systems can be designed with either soft starter or VFDs at **3.51 MW**. The transformers can be placed at both portals.

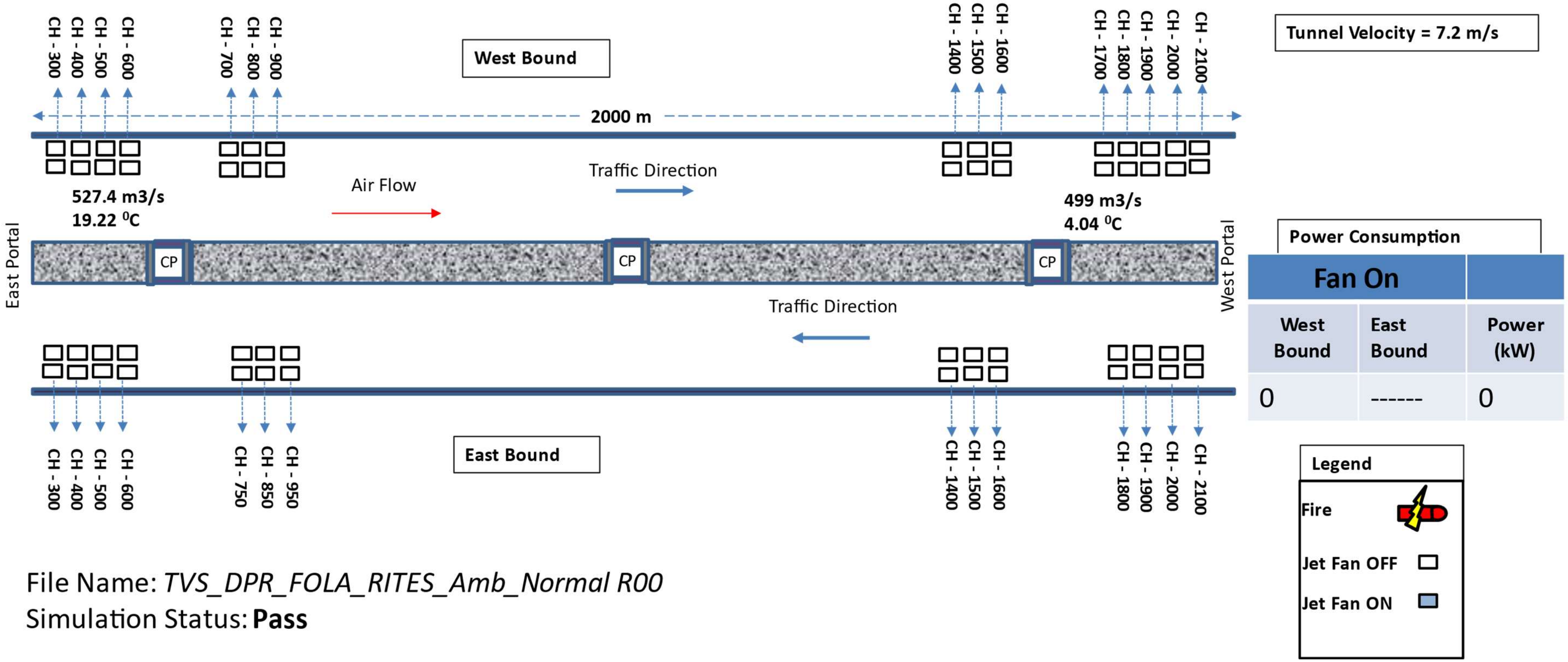
12 APPENDIX I - NORMAL MODE: FOTU LA TUNNEL

Following is the electrical load summary for the normal operation scenario.

Table 11: Operation mode for normal operation

Tunnel	**Mode**	**Operating kW**	**No of Operating Tunnel Fan**
West Bound	**Mode 1**	0	0
East Bound		0	0

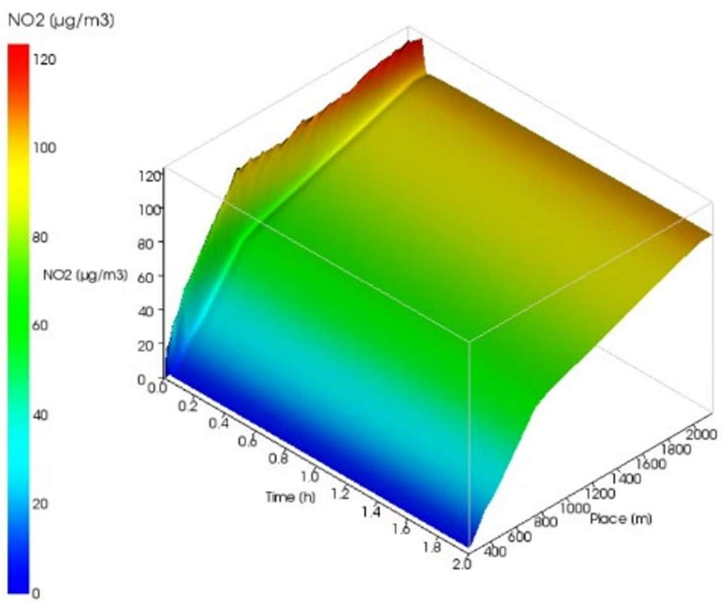
Normal Mode – West Bound



File Name: *TVS_DPR_FOLA_RITES_Amb_Normal R00*
Simulation Status: **Pass**

Figure 12: Fotu La Tunnel Normal Operation Mode -Mode 1

Nitrogen Dioxide Level

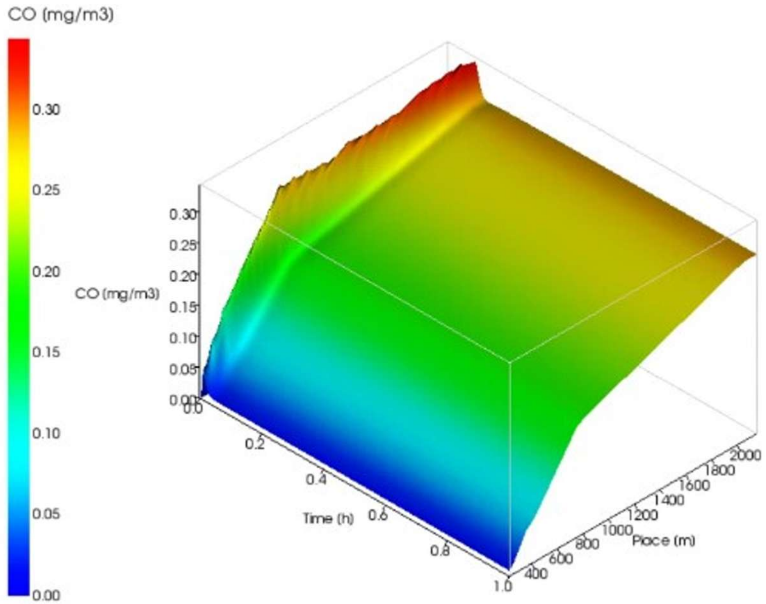


Contour plot

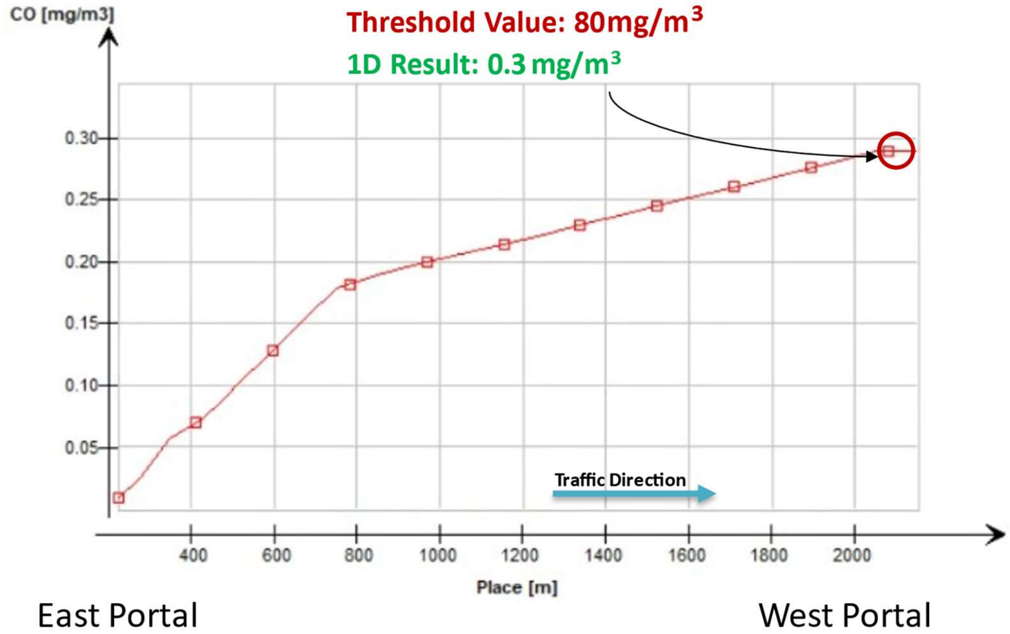
NO2 along the tunnel

Figure 13: NO_2 Level Fotu la Tunnel – Mode 1

Carbon Mono Oxide Level



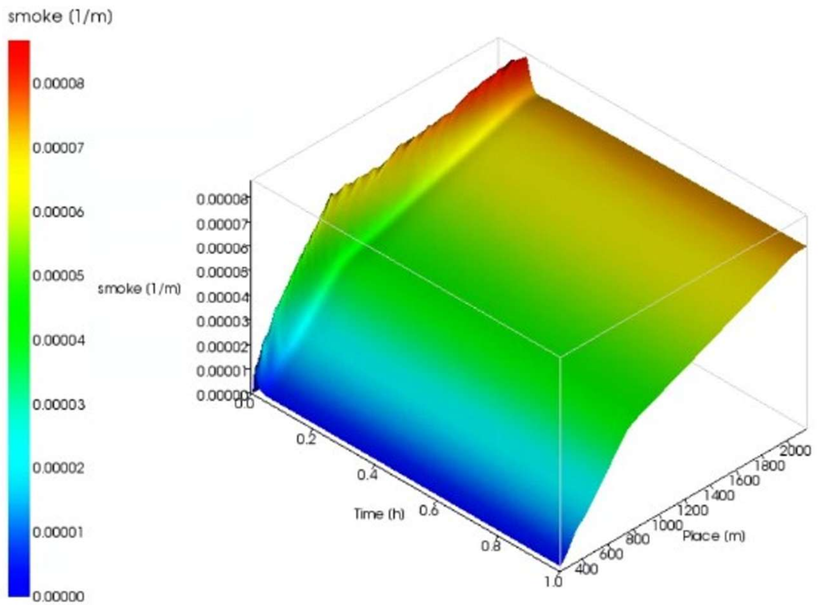
Contour plot



CO along the tunnel

Figure 14: CO Level Fotu la Tunnel – Mode 1

Extinction Coefficient Level

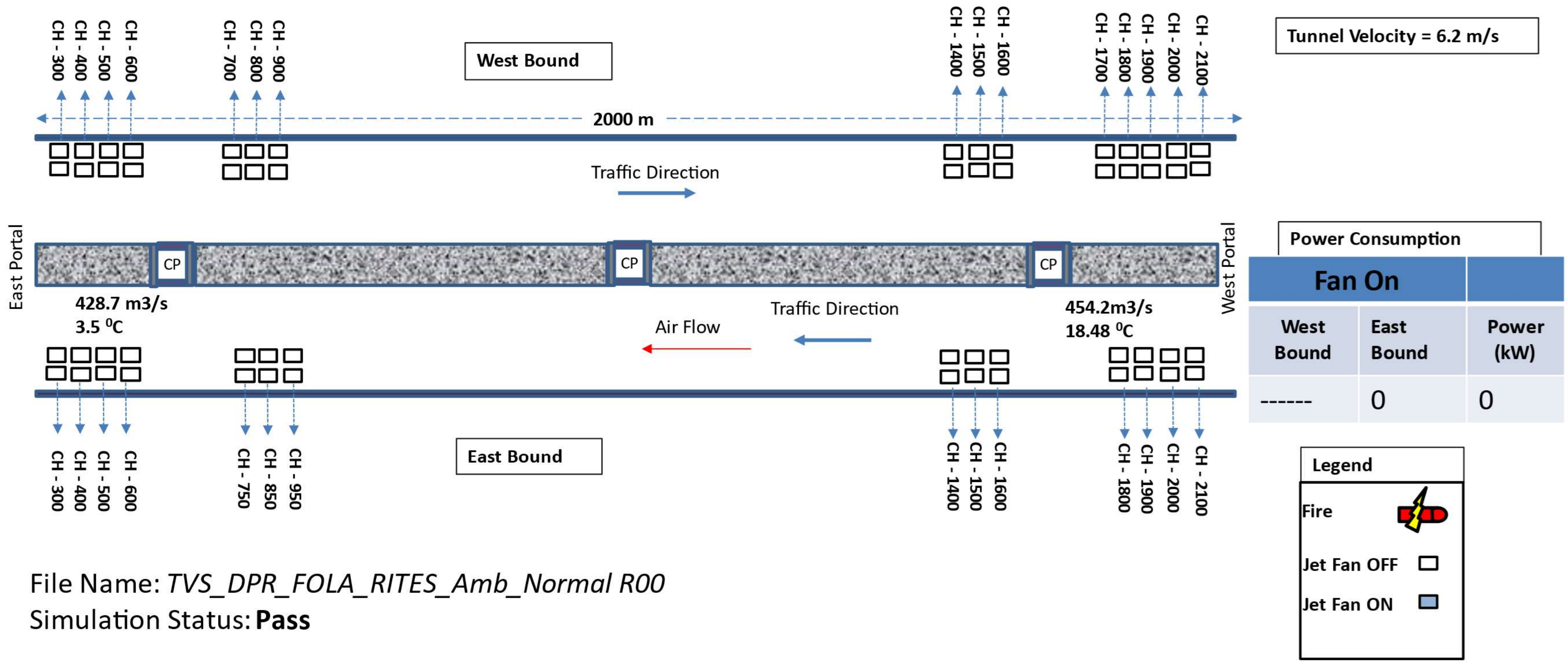


Contour plot

Extinction Coefficient along the tunnel

Figure 15: Extinction Coefficient Level Fotu la Tunnel – Mode 1

Normal Mode – East Bound

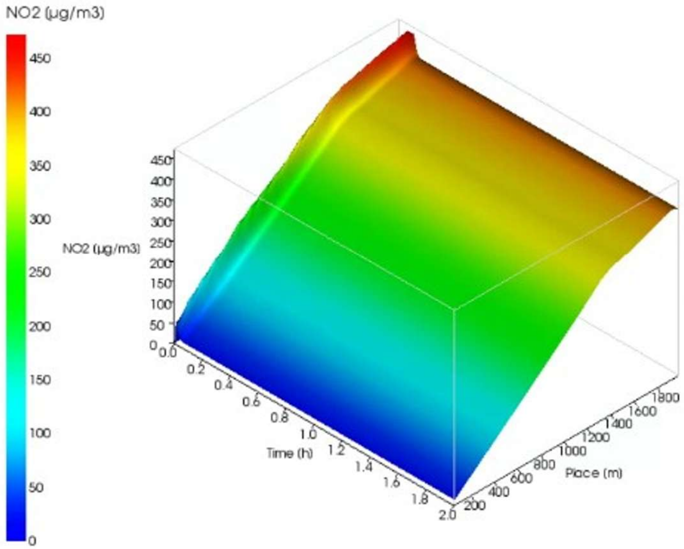


Fan On		
West Bound	East Bound	Power (kW)
------	0	0

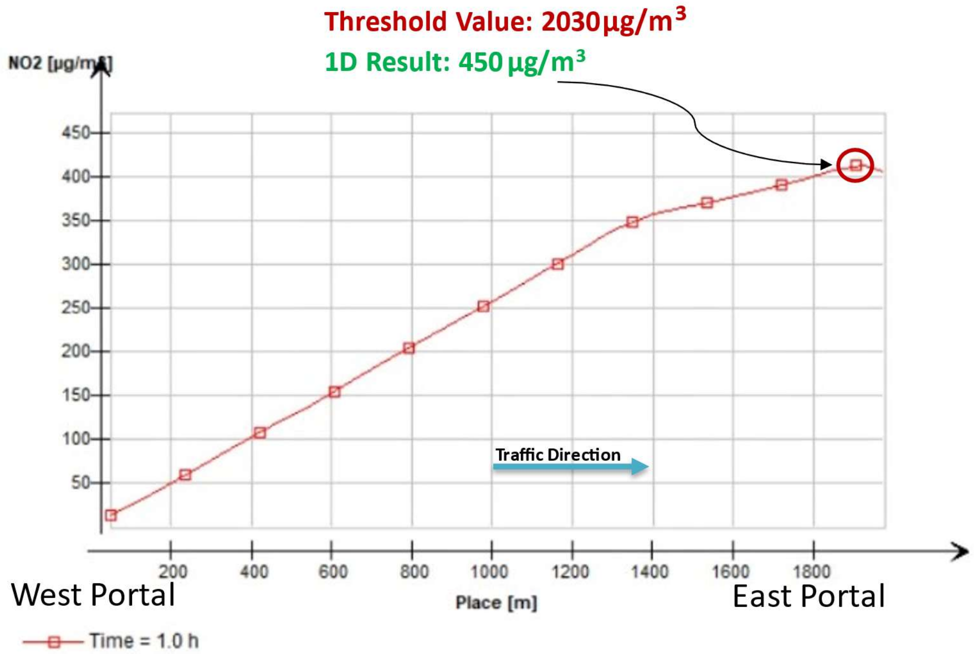
File Name: *TVS_DPR_FOLA_RITES_Amb_Normal R00*
Simulation Status: **Pass**

Figure 16: Fotu La Tunnel Normal Operation Mode -Mode 1

Nitrogen Dioxide Level



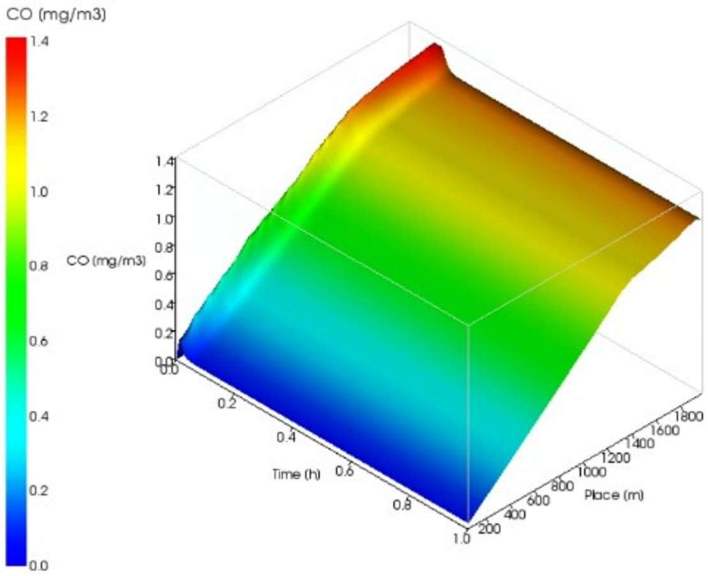
Contour plot



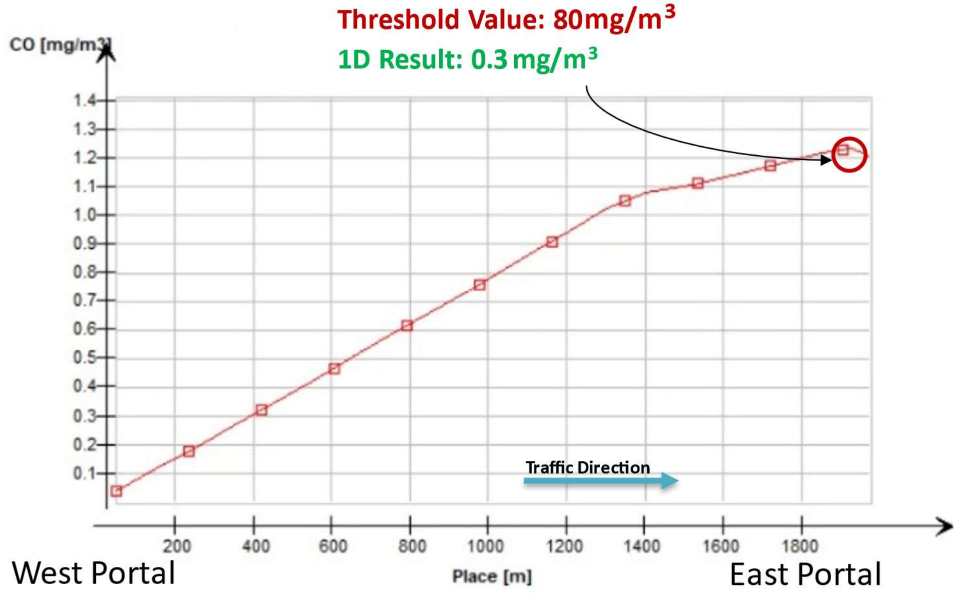
NO2 along the tunnel

Figure 17: NO2 Level Fotu la Tunnel – Mode 1

Carbon Mono Oxide Level



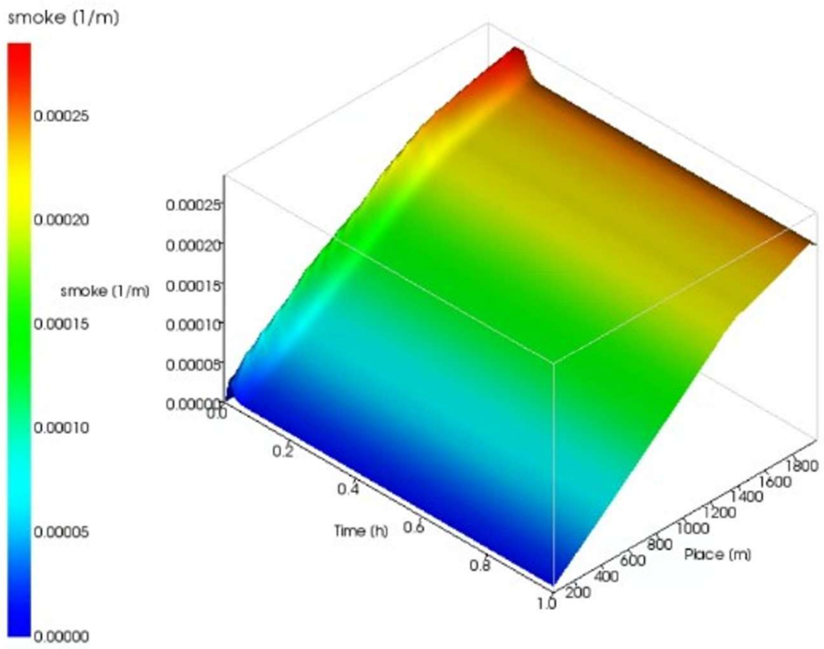
Contour plot



CO along the tunnel

Figure 18: CO Level Fotu la Tunnel – Mode 1

Extinction Coefficient Level



Contour plot

Extinction Coefficient along the tunnel

Figure 19: CO Level Fotu la Tunnel – Mode 1

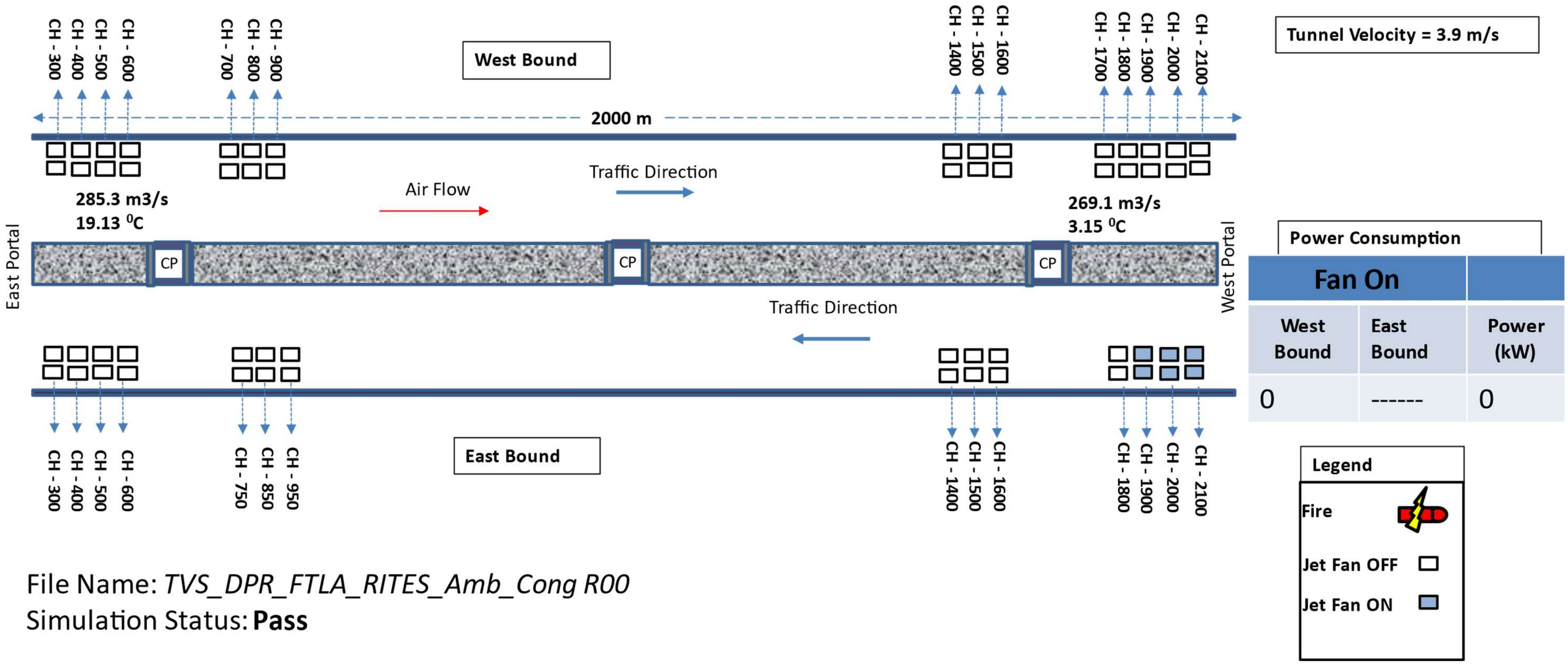
13 APPENDIX II - CONGESTION MODE: FOTU LA TUNNEL

Following is the operating electrical load summary of congestion operation scenario.

Table 12: Operation mode for congestion operation

Tunnel	Mode	Operating KW	No of Operating Tunnel Fan
West Bound	**Mode 2**	0	0
East Bound		450	6

Congestion Mode – West Bound

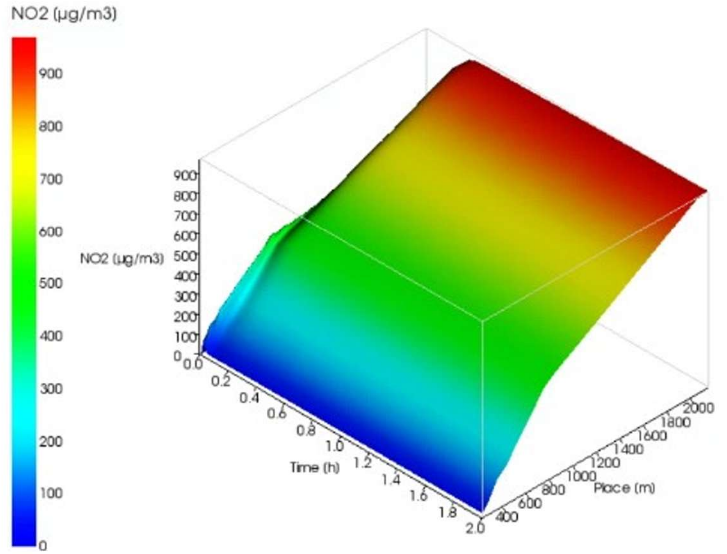


File Name: *TVS_DPR_FTLA_RITES_Amb_Cong R00*

Simulation Status: **Pass**

Figure 20: Fotu La Tunnel Congestion Operation Mode for West Bound -Mode 2

Nitrogen Dioxide Level

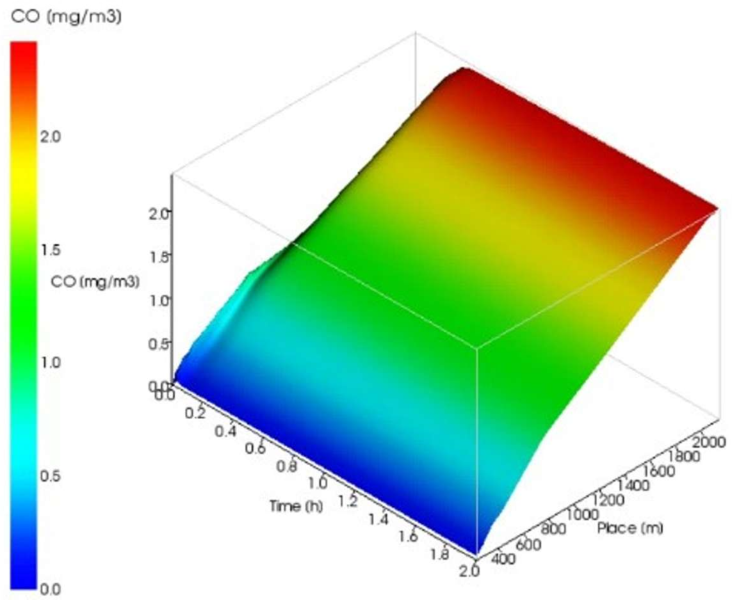


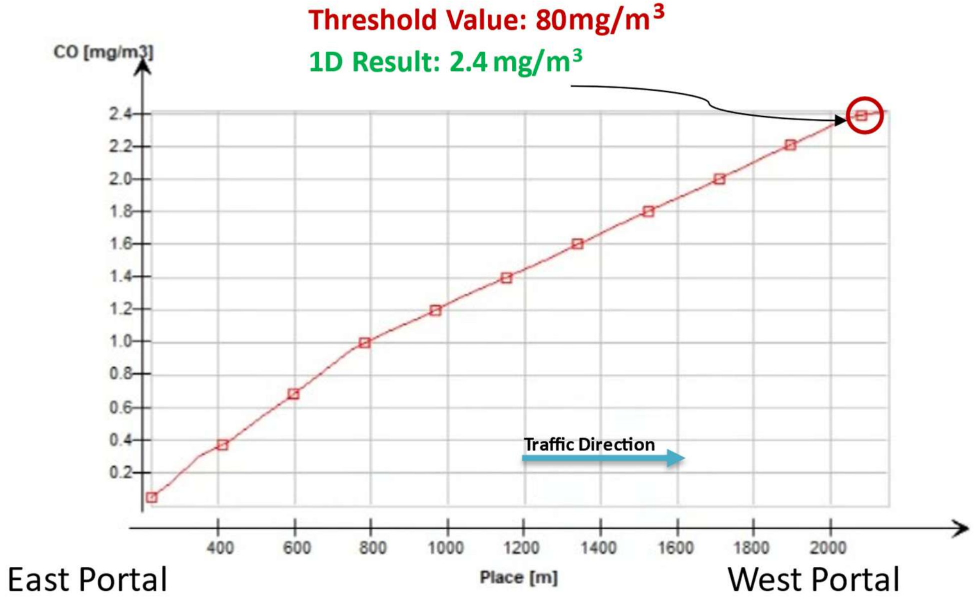
Contour plot

NO2 along the tunnel

Figure 21: NO2 Level Fotu la Tunnel – Mode 2

Carbon Mono Oxide Level

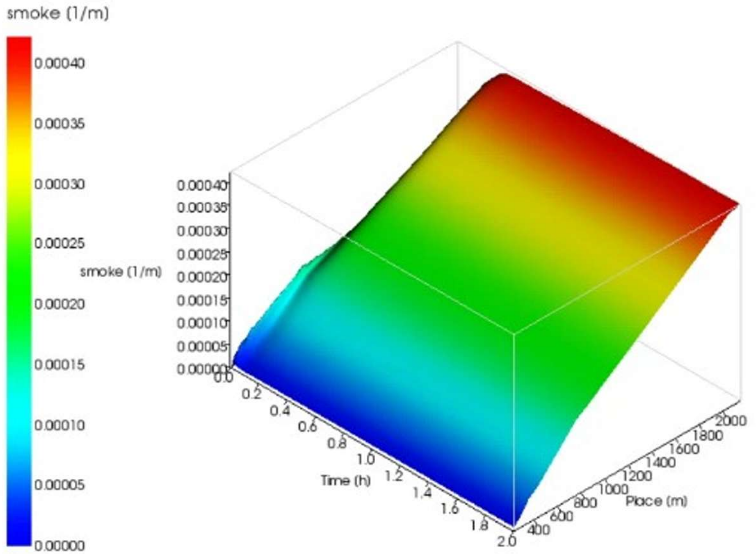




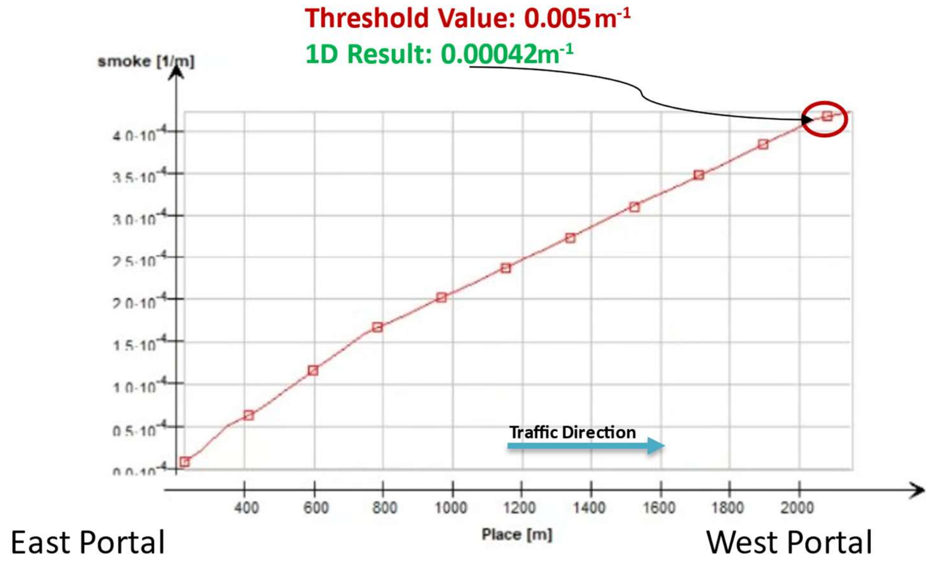
Contour plot **CO along the tunnel**

Figure 22: CO Level Fotu la Tunnel – Mode 2

Extinction Coefficient Level



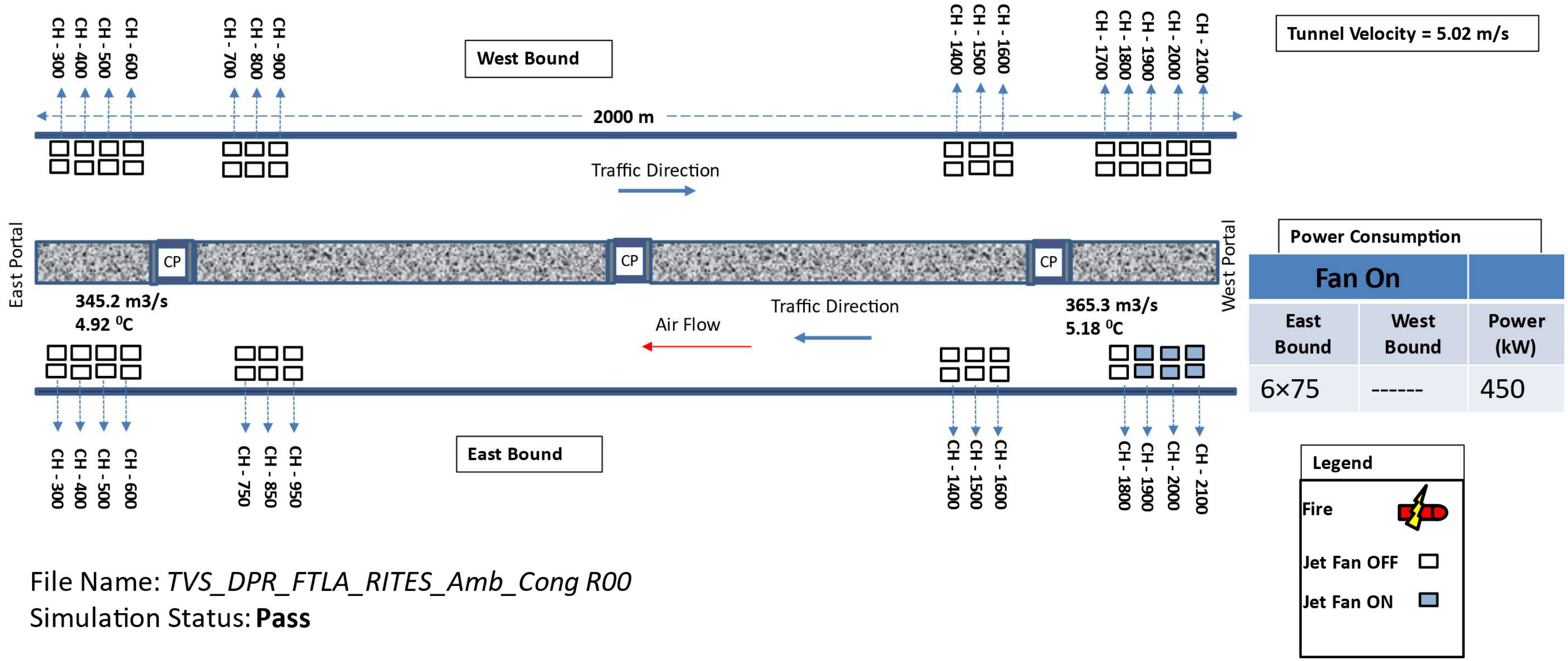
Contour plot



Extinction Coefficient along the tunnel

Figure 23: Extinction Coefficient Level Fotu la Tunnel – Mode 2

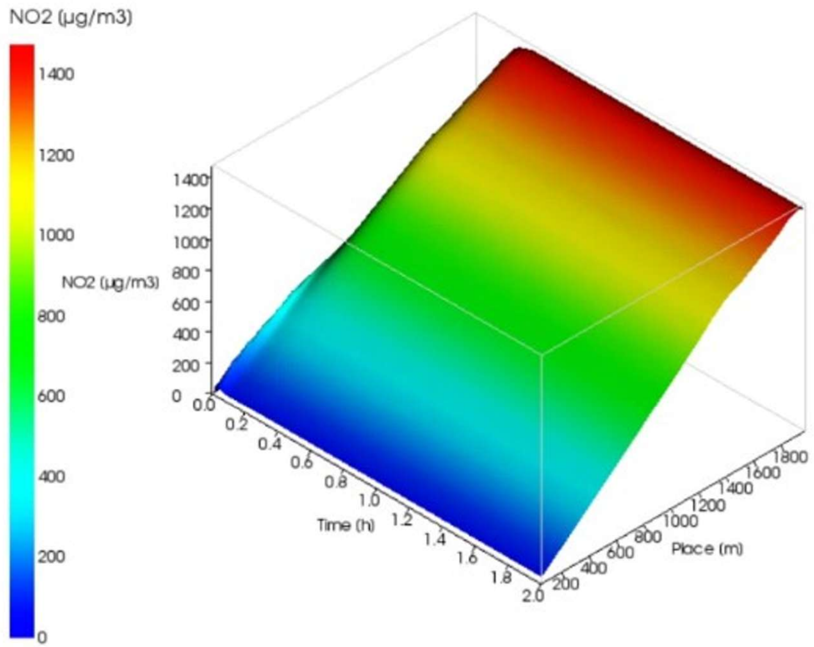
Congestion Mode – East Bound



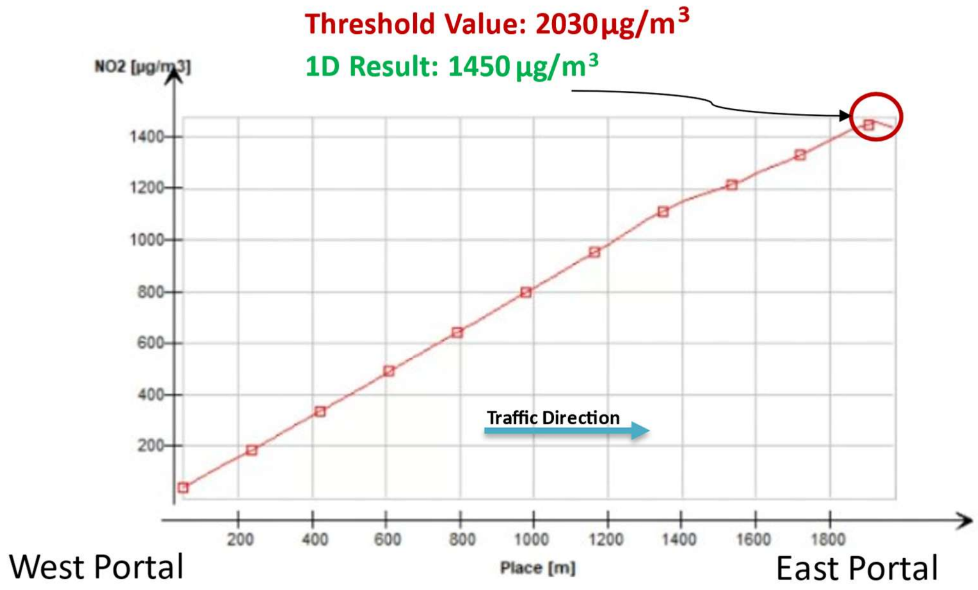
File Name: *TVS_DPR_FTLA_RITES_Amb_Cong R00*
Simulation Status: **Pass**

Figure 24: Fotu La Tunnel Congestion Operation Mode for East Bound -Mode 2

Nitrogen Dioxide Level



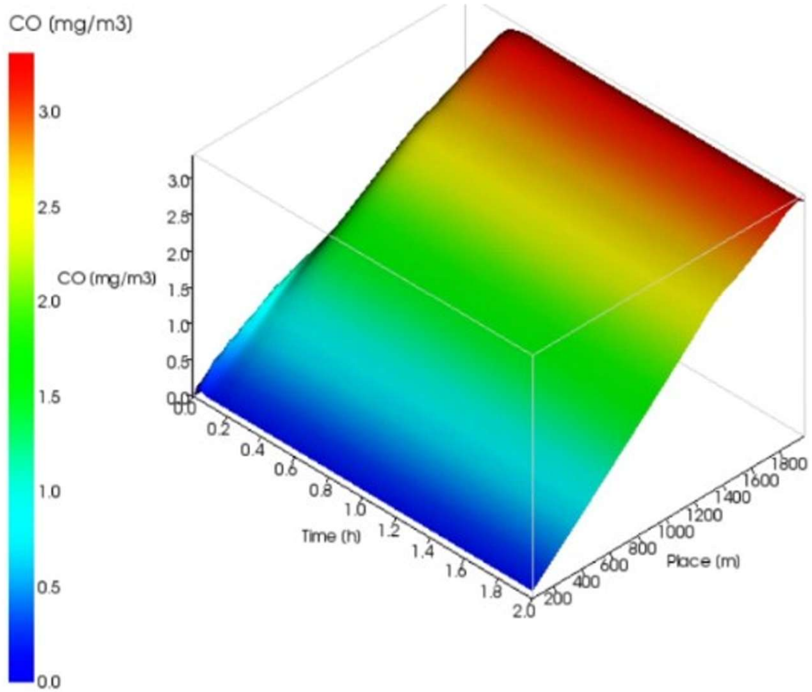
Contour plot



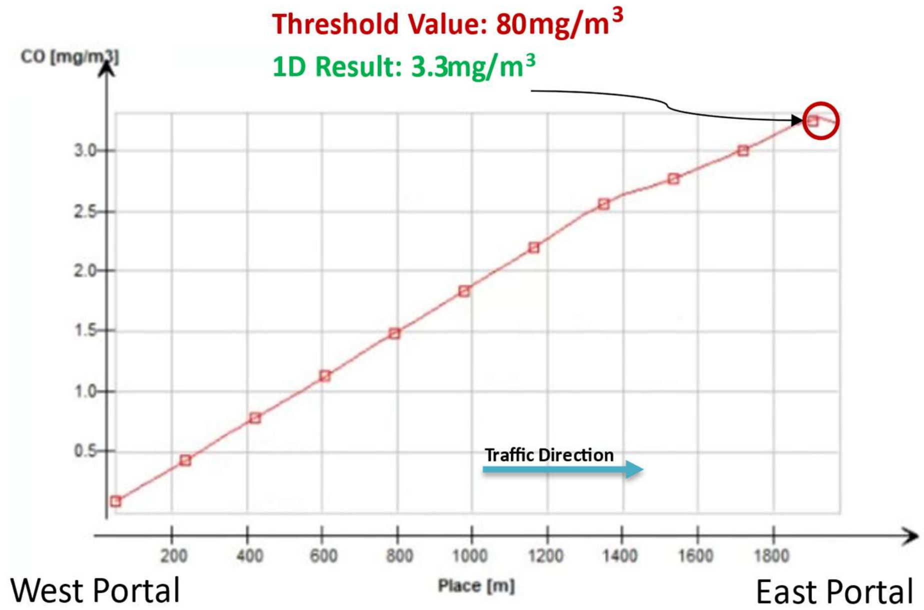
NO2 along the tunnel

Figure 25: NO2 Level Fotu la Tunnel – Mode 2

Carbon Mono Oxide Level



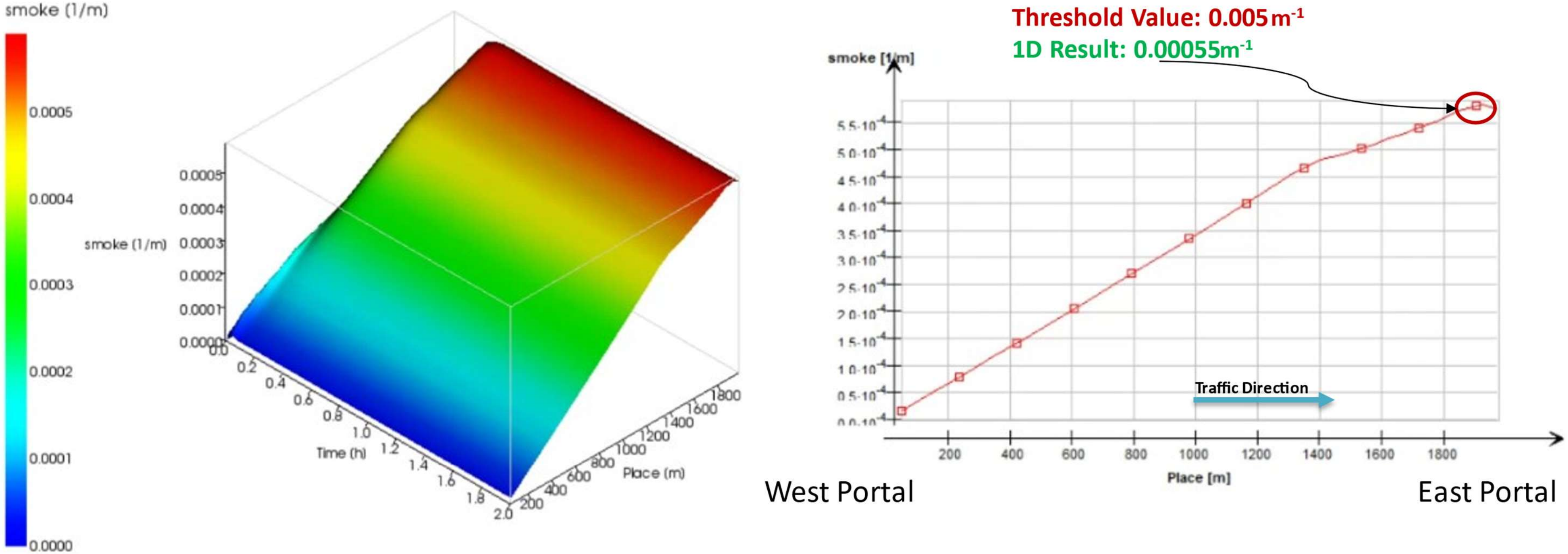
Contour plot



CO along the tunnel

Figure 26: CO Level Fotu la Tunnel – Mode 2

Extinction Coefficient Level



Contour plot **Extinction Coefficient along the tunnel**

Figure 27: Extinction Coefficient Level Fotu la Tunnel – Mode 2

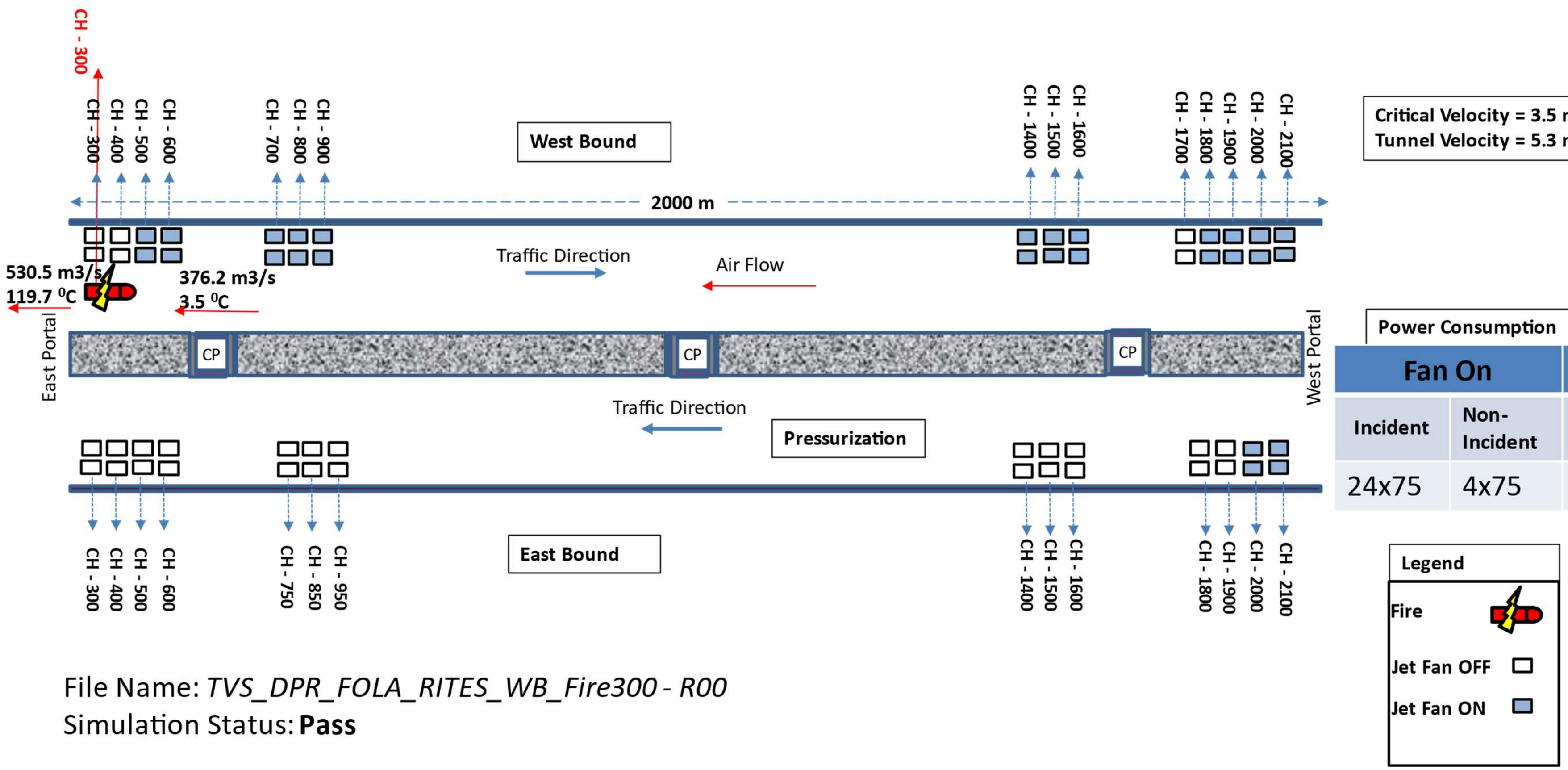
14 APPENDIX III - EMERGENCY MODE: FOTU LA TUNNEL

Following table shows electrical load summary for different emergency operation scenario considered.

Table 13: Summary table of ventilation mode in Emergency operation.

Tunnel	Mode	Fire Location	Fans Operating in incident Tunnel	Fans Operating in Non-incident Tunnel	Operating kW	Critical Velocity	Tunnel Velocity
West Bound	Mode 3	CH:300	24	4	2100	3.5	5.3
	Mode 4	CH:1000	28	4	2400	3.78	5.15
	Mode 5	CH:2000	22	14	2700	3.78	4.87
West Bound	Mode 6	CH:300	24	12	2700	3.5	4.8
	Mode 7	CH:1000	26	8	2550	3.43	4.85
	Mode 8	CH:2000	20	8	2100	3.78	4.74

Emergency Mode – West Bound @CH:300

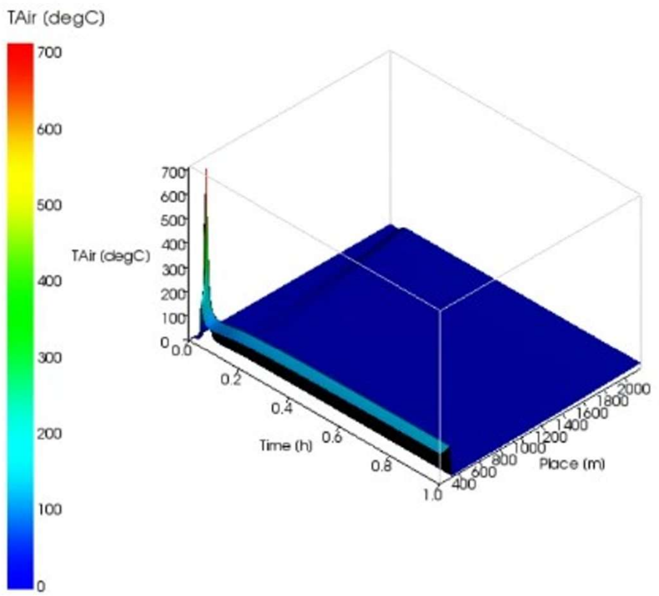


Fan On		
Incident	Non-Incident	Power (kW)
24x75	4x75	2100

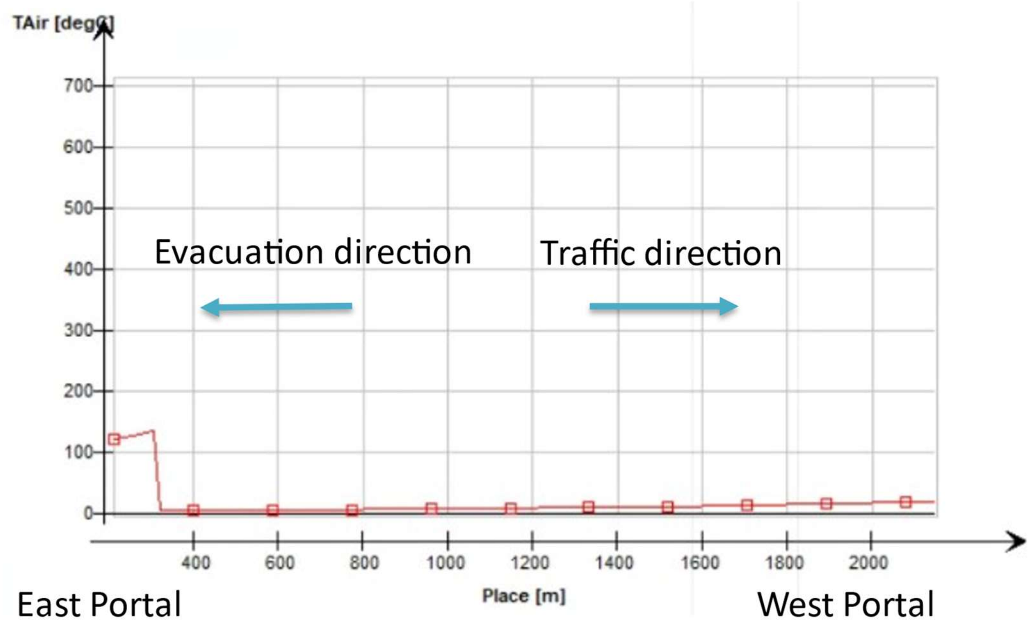
File Name: *TVS_DPR_FOLA_RITES_WB_Fire300 - R00*
Simulation Status: **Pass**

Figure 28: Fotu La Tunnel Emergency Operation Mode for West Bound -Mode 3

Air Temperature



Contour plot



Air Temperature along the tunnel

Figure 29: Air Temperature for West Bound, Fotu la Tunnel – Mode 3

Smoke Extinction Level

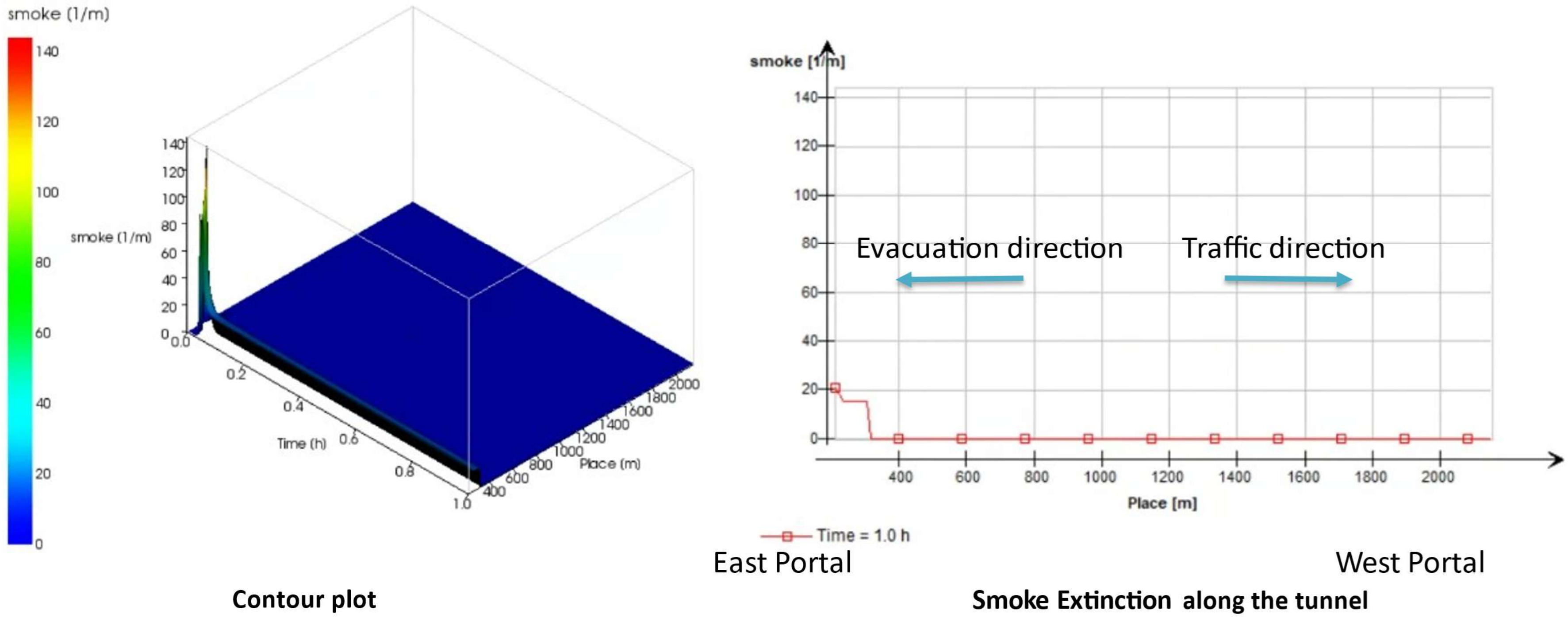


Figure 30: Smoke Extinction for West Bound, Fotu la Tunnel – Mode 3

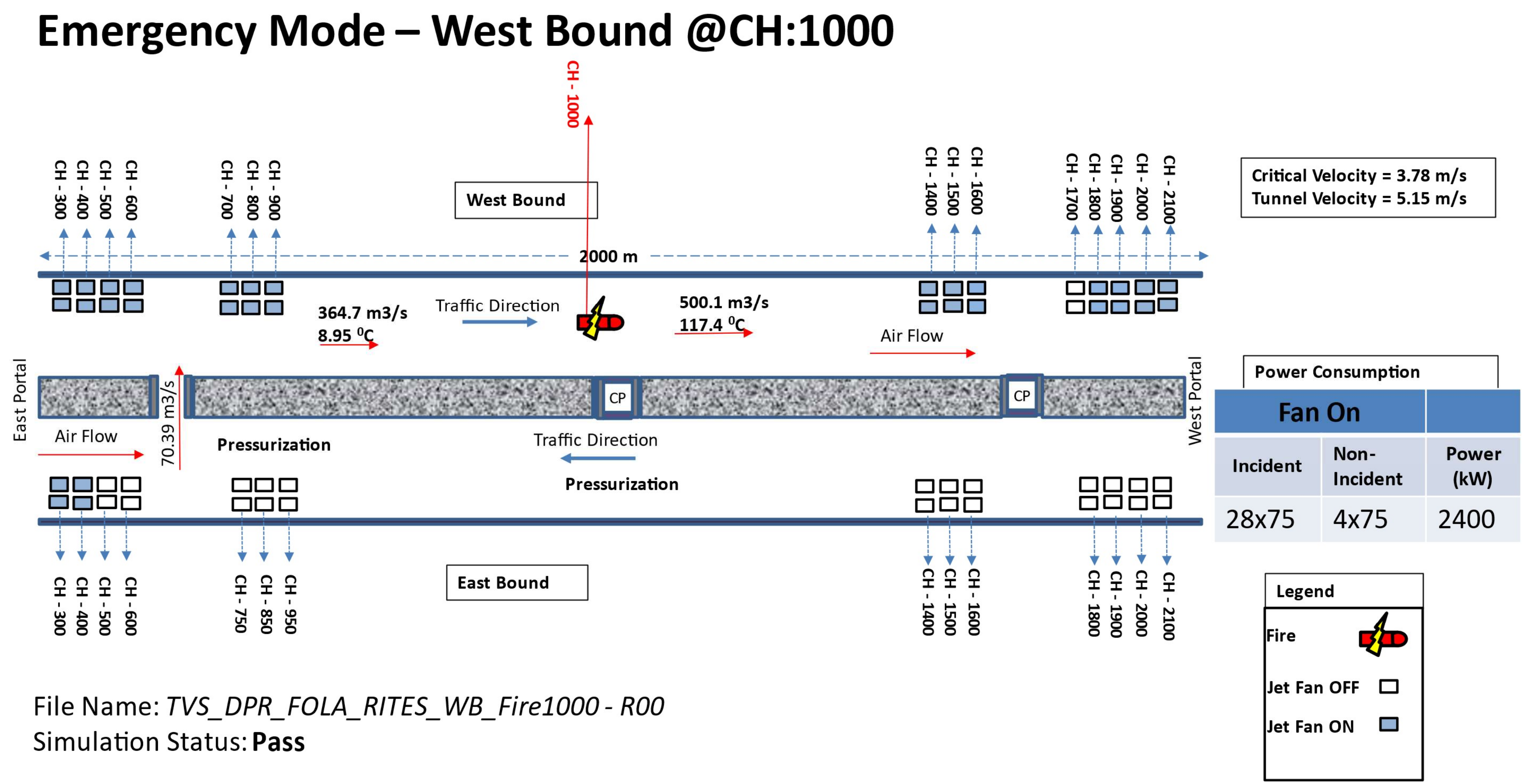


Figure 31: Fotu La Tunnel Emergency Operation Mode for West Bound -Mode 4

Air Temperature

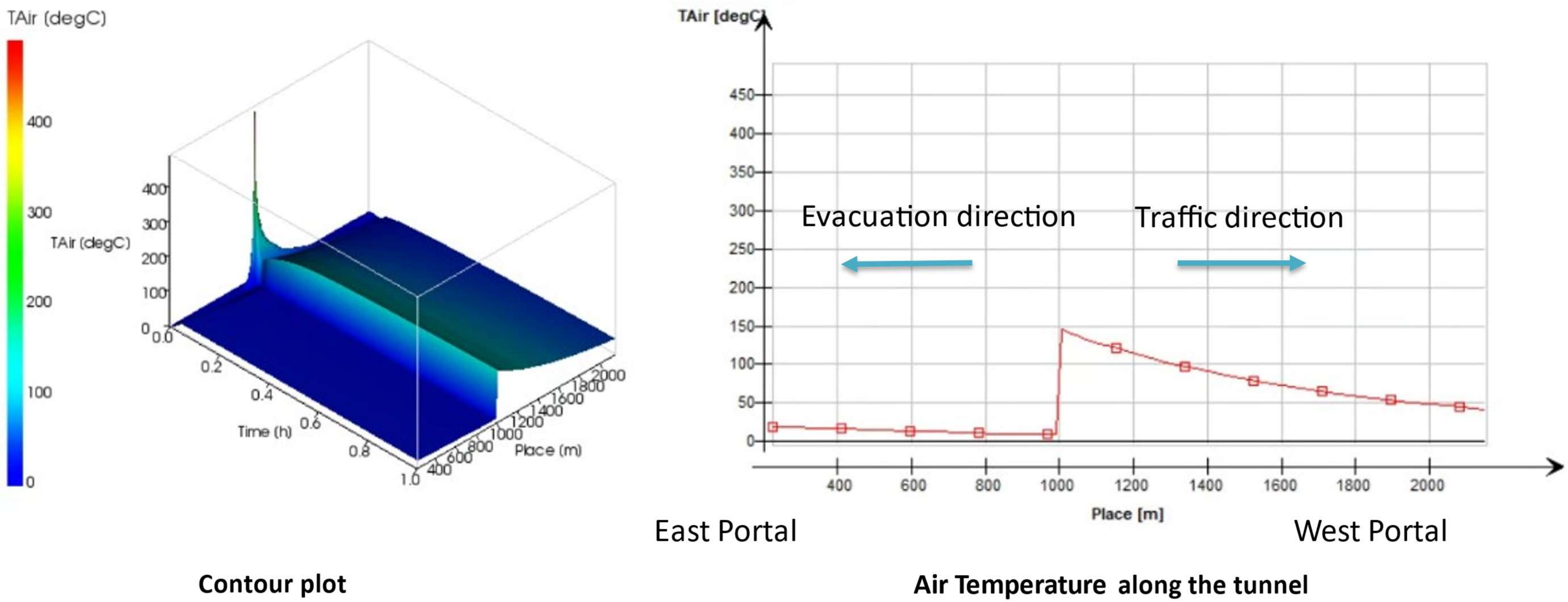


Figure 32: Air Temperature for West Bound, Fotu la Tunnel – Mode 4

Smoke Extinction Level

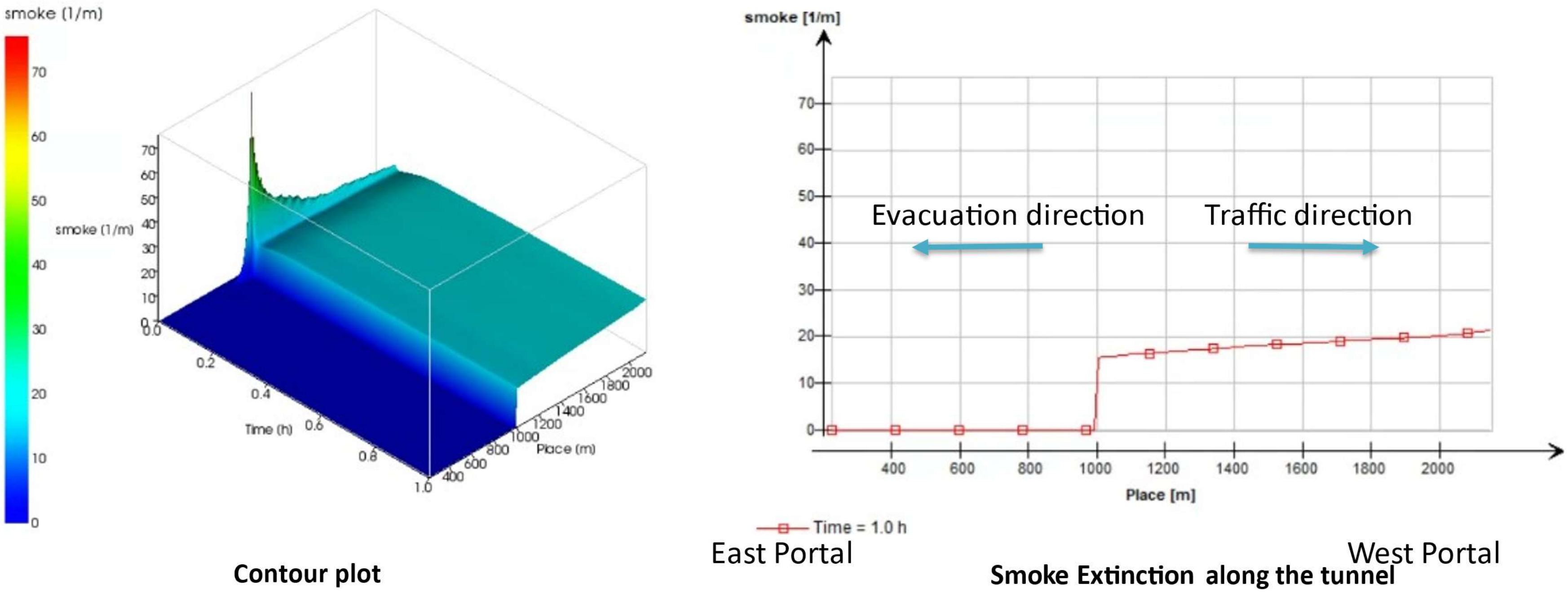


Figure 33: Smoke Extinction for West Bound, Fotu la Tunnel – Mode 4

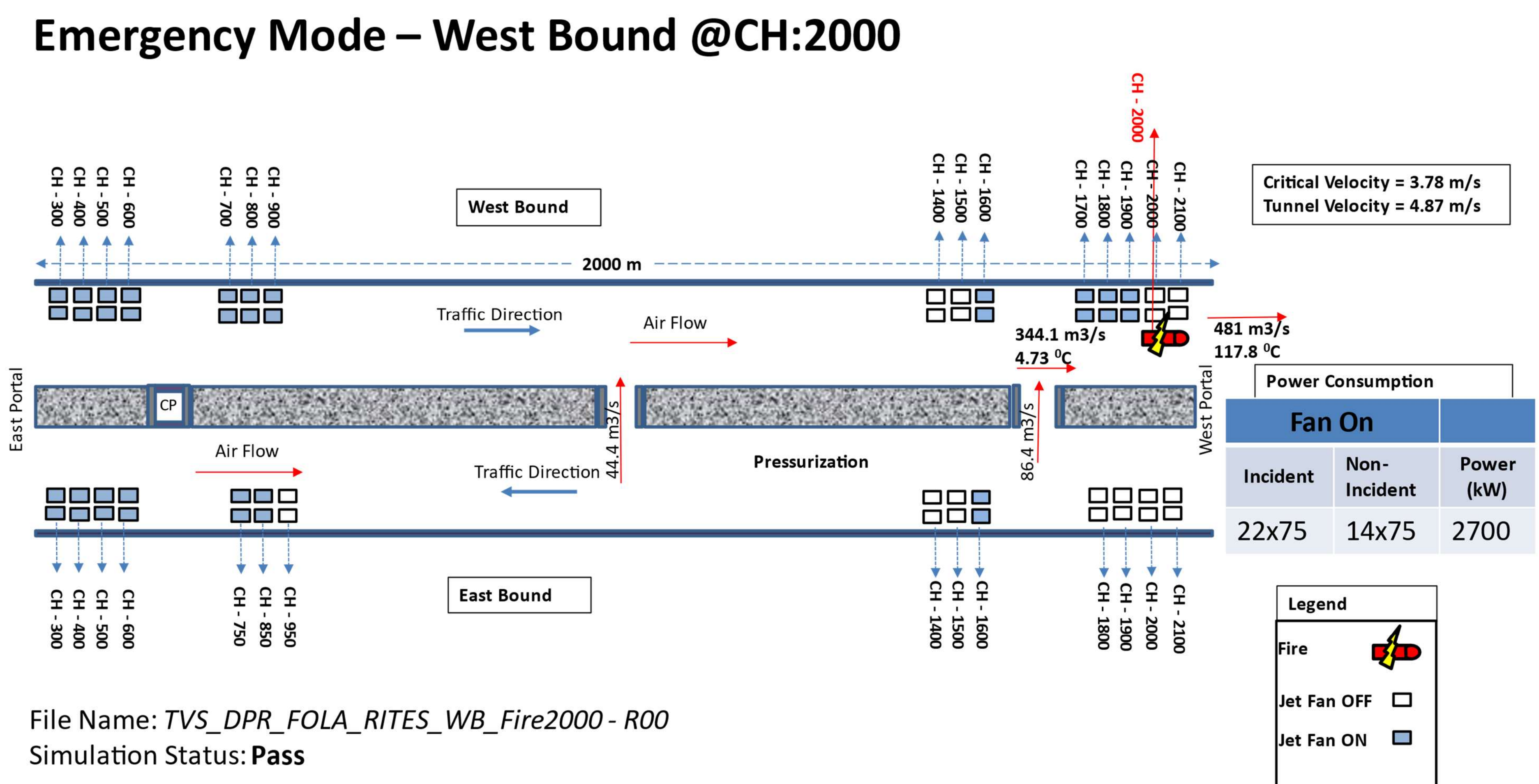
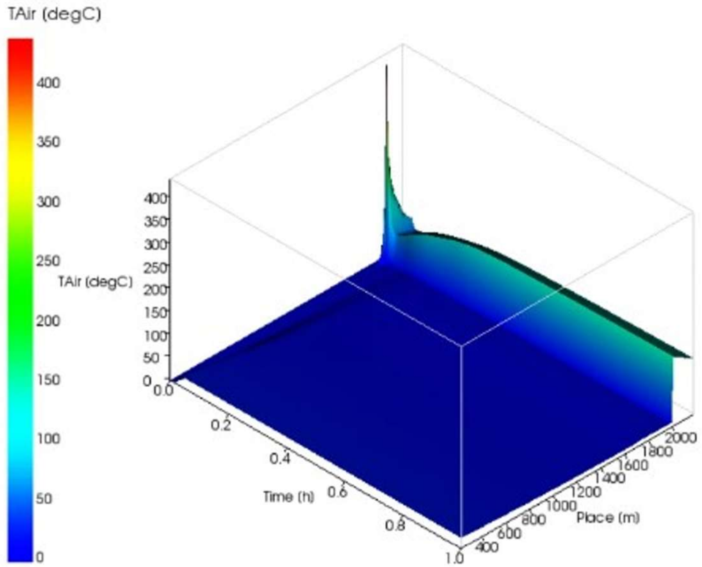
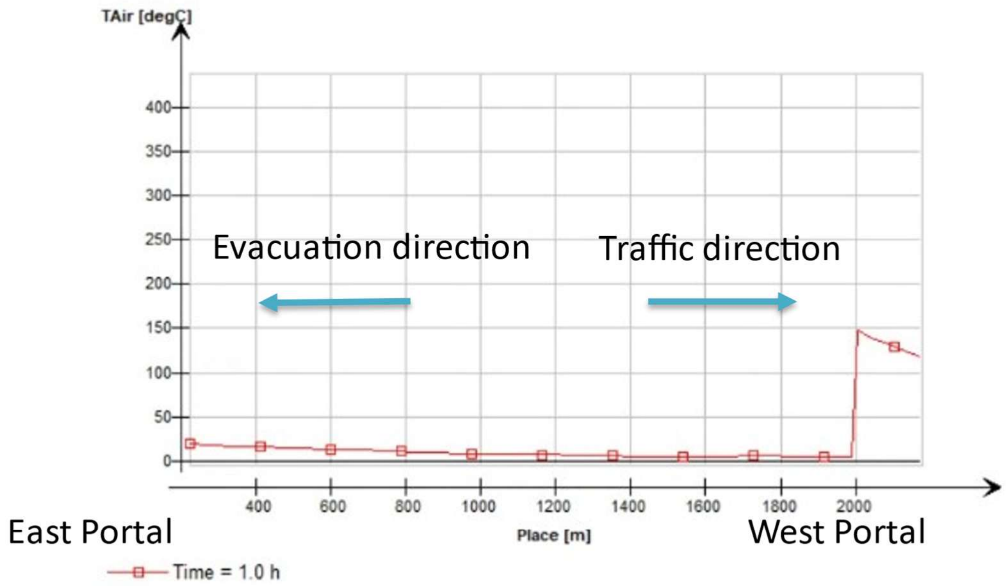


Figure 34: Fotu La Tunnel Emergency Operation Mode for West Bound -Mode 5

Air Temperature



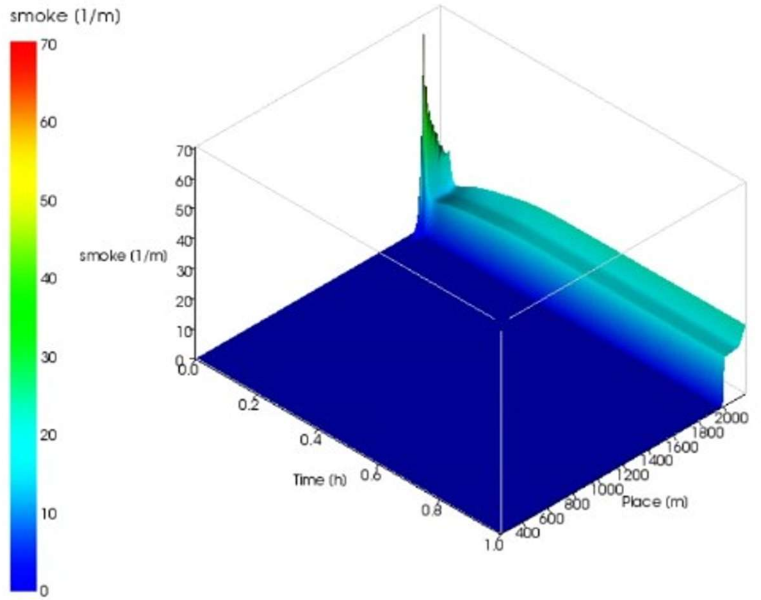


Contour plot

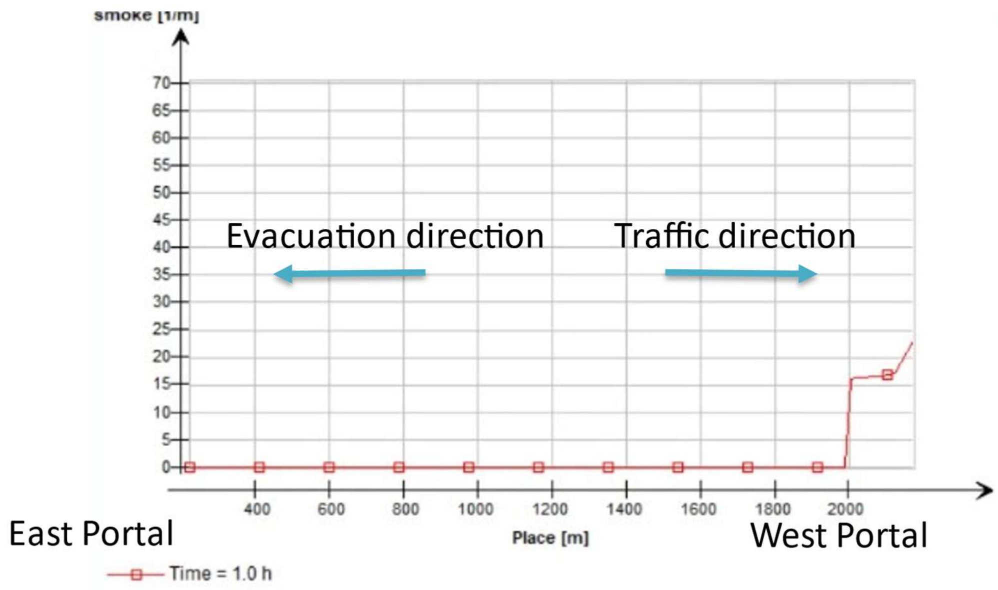
Air Temperature along the tunnel

Figure 35: Air Temperature for West Bound, Fotu la Tunnel – Mode 5

Smoke Extinction Level



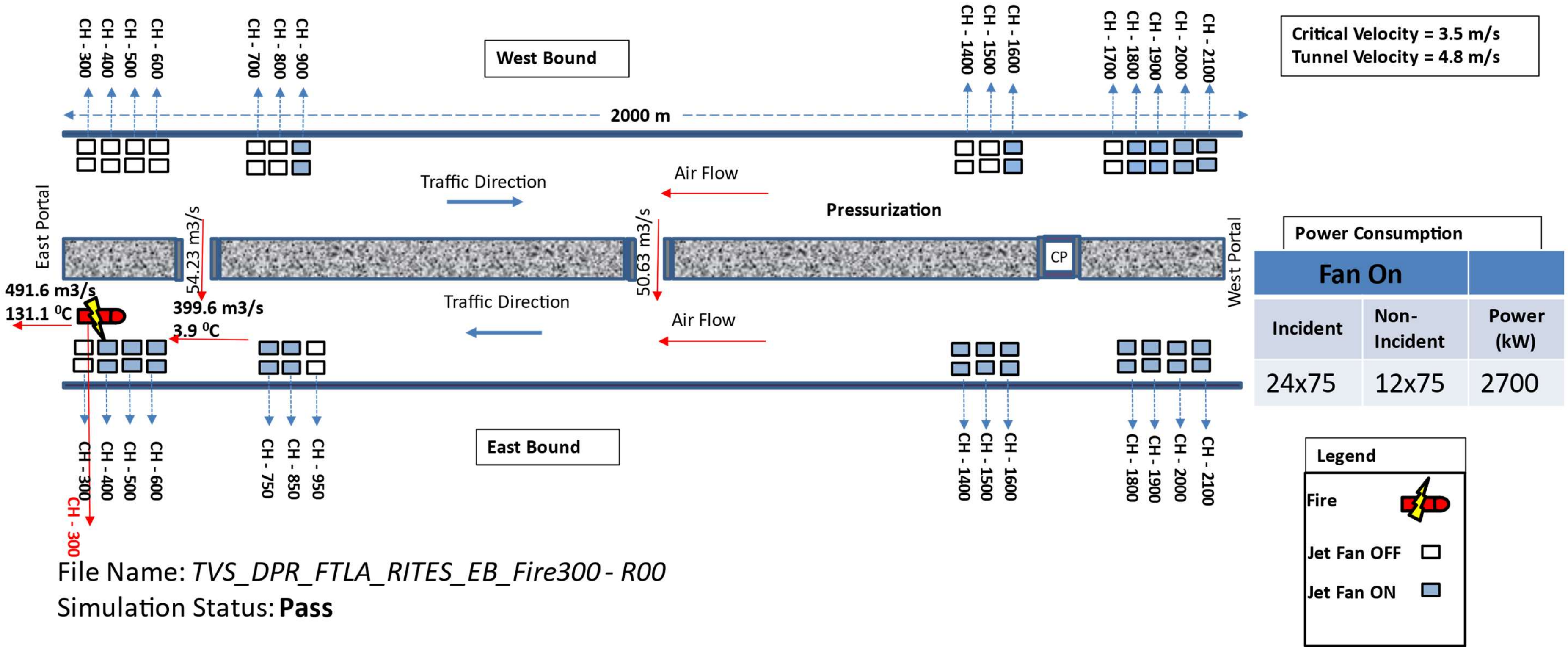
Contour plot



Smoke Extinction along the tunnel

Figure 36: Smoke Extinction for West Bound, Fotu la Tunnel – Mode 5

Emergency Mode – East Bound @CH:300



Fan On		
Incident	Non-Incident	Power (kW)
24x75	12x75	2700

File Name: *TVS_DPR_FTLA_RITES_EB_Fire300 - R00*
Simulation Status: **Pass**

Figure 37: Fotu La Tunnel Emergency Operation Mode for East Bound -Mode 6

Air Temperature

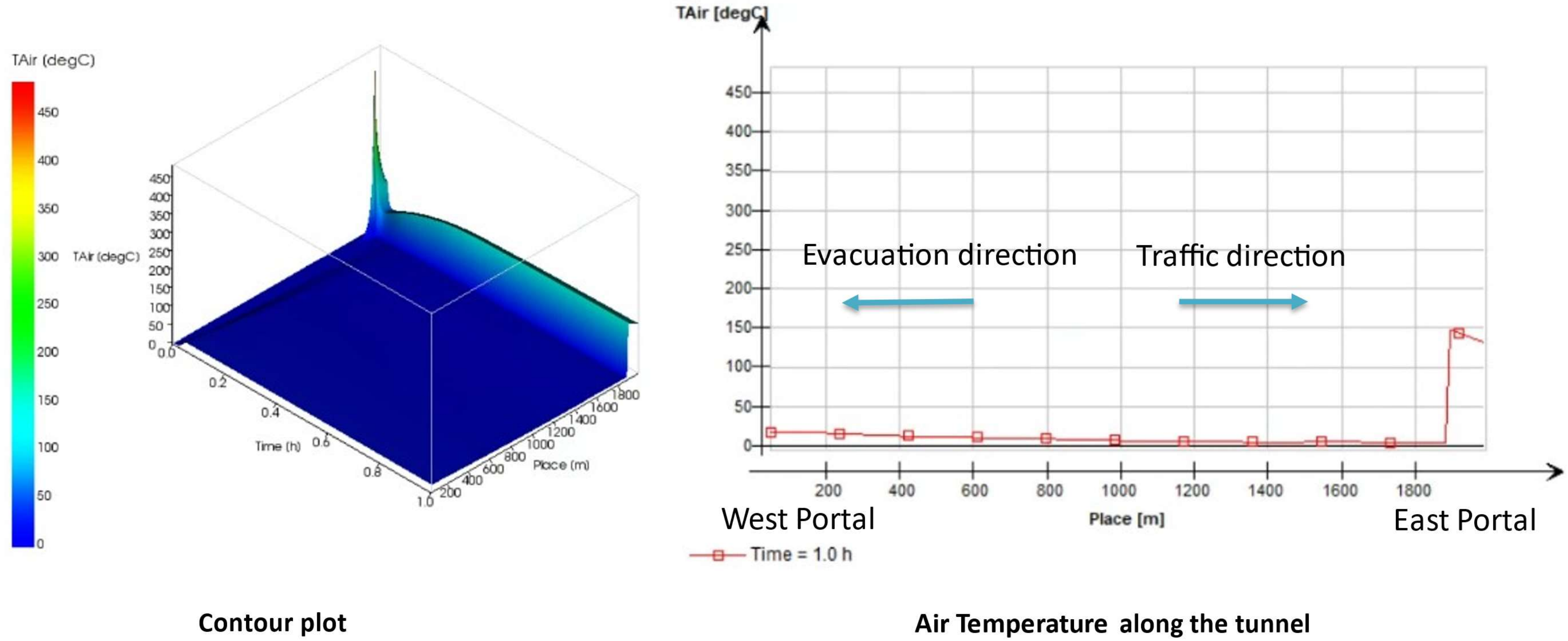
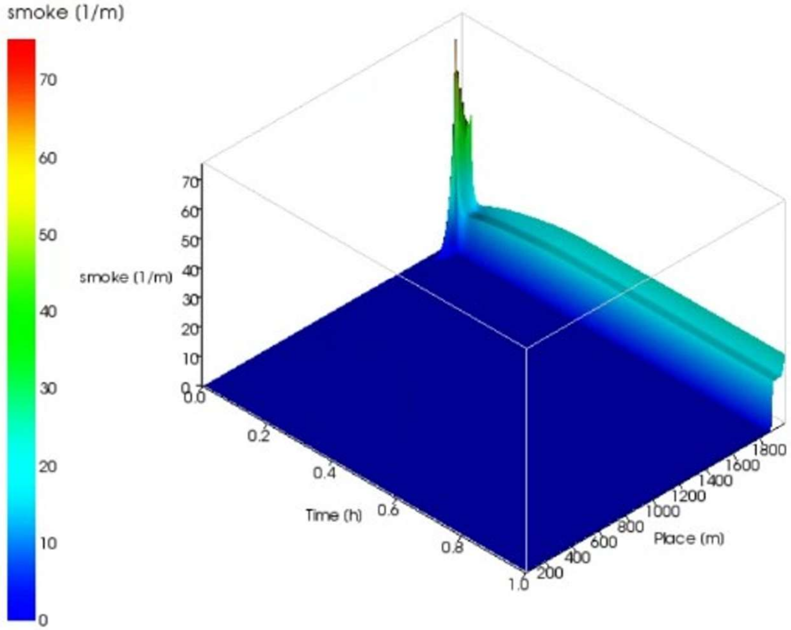
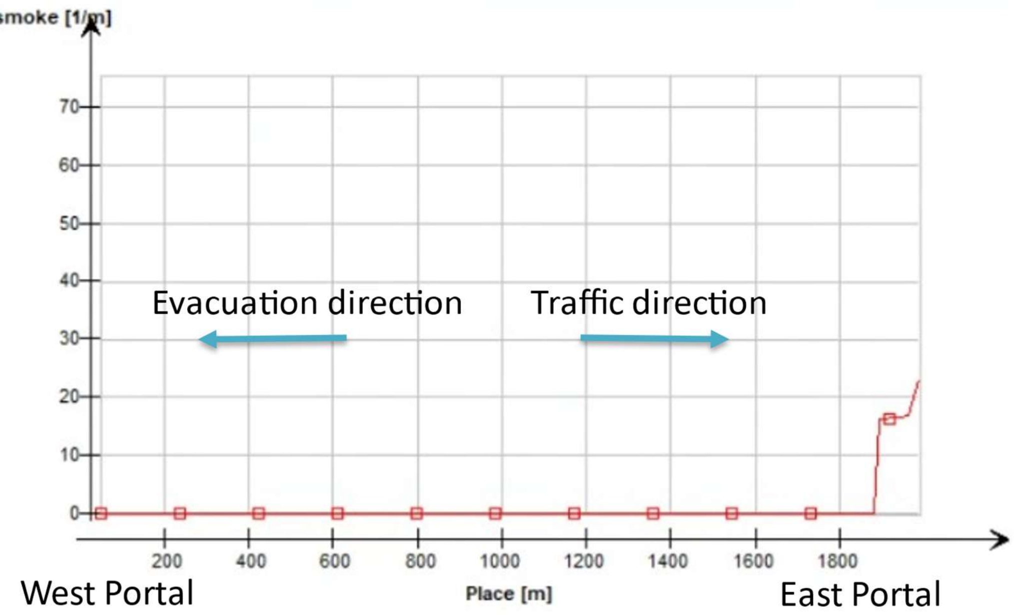


Figure 38: Air Temperature for East Bound, Fotu la Tunnel – Mode 6

Smoke Extinction Level



Contour plot



Smoke Extinction along the tunnel

Figure 39: Smoke Extinction for East Bound, Fotu la Tunnel – Mode 6

Emergency Mode – East Bound @CH:1000

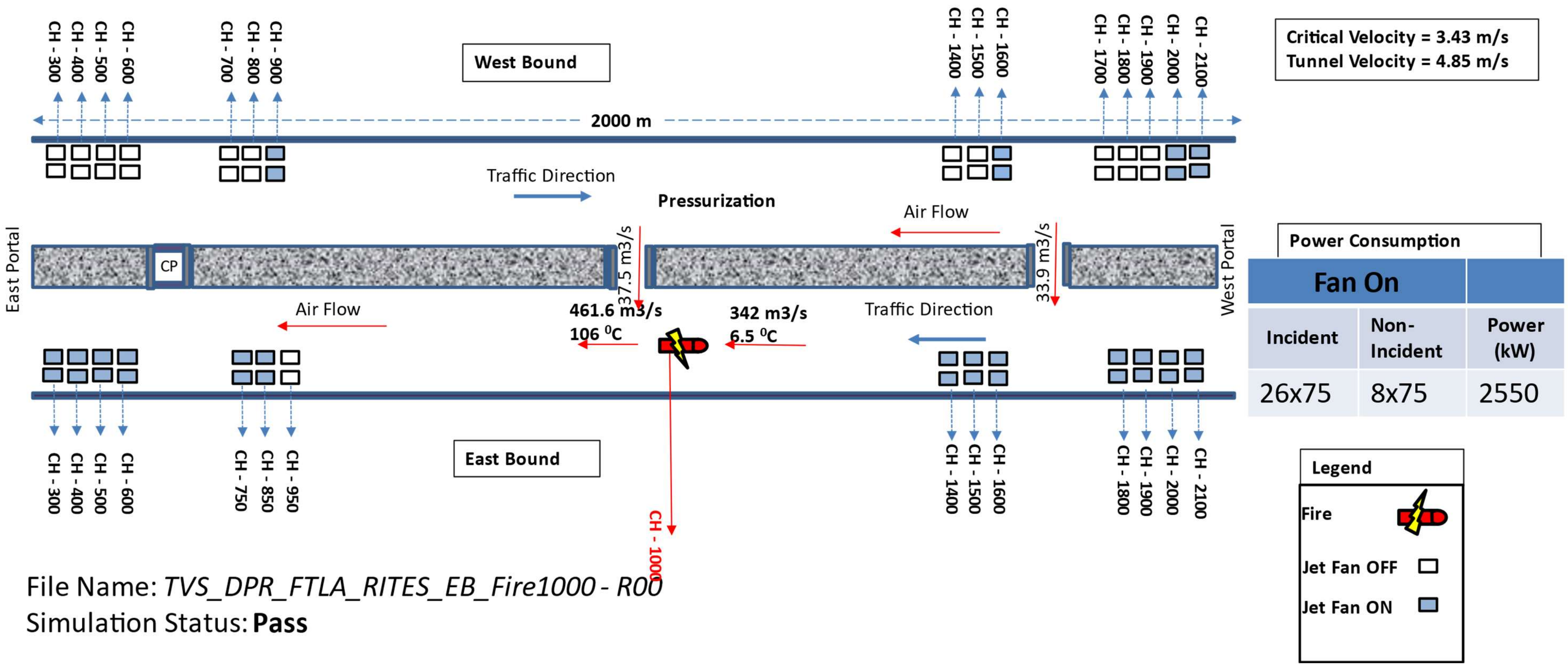
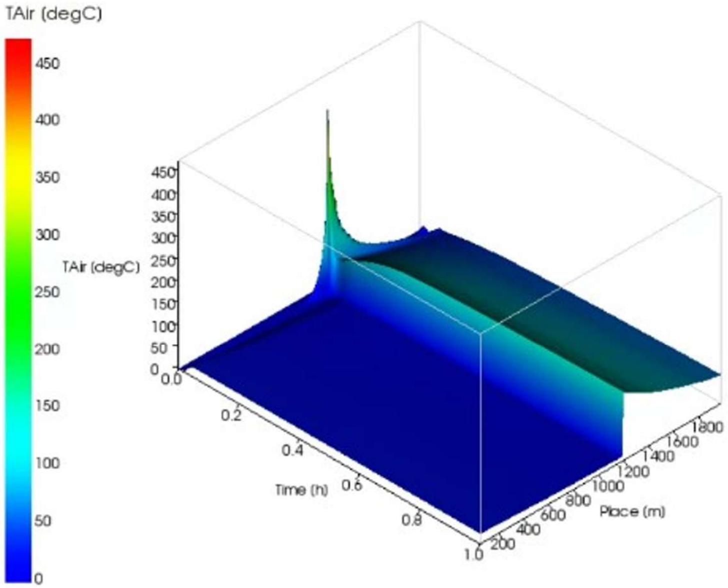
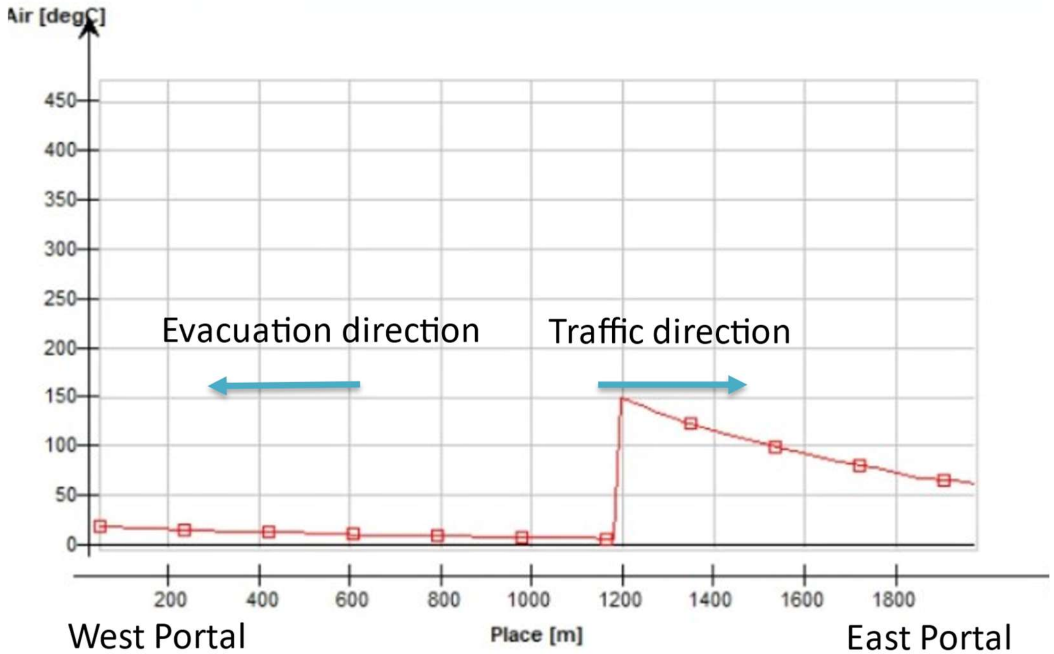


Figure 40: Fotu La Tunnel Emergency Operation Mode for East Bound -Mode 7

Air Temperature



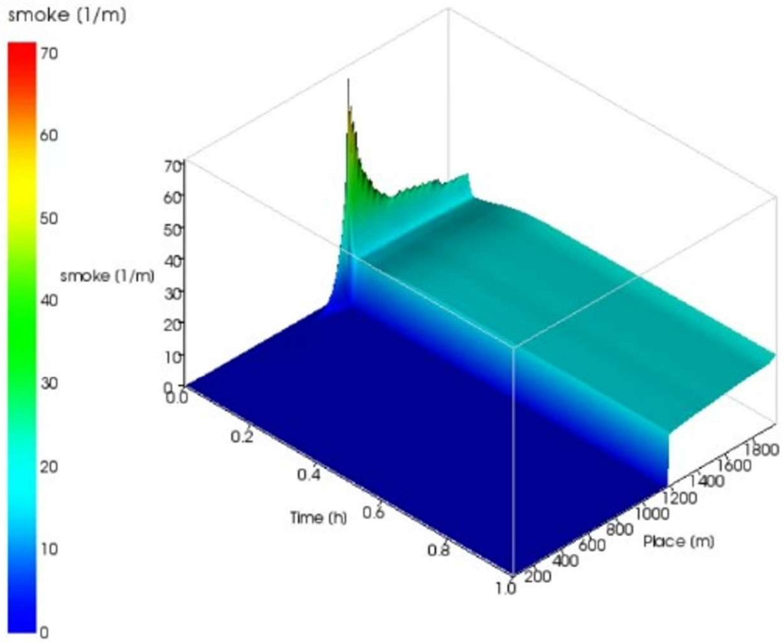
Contour plot



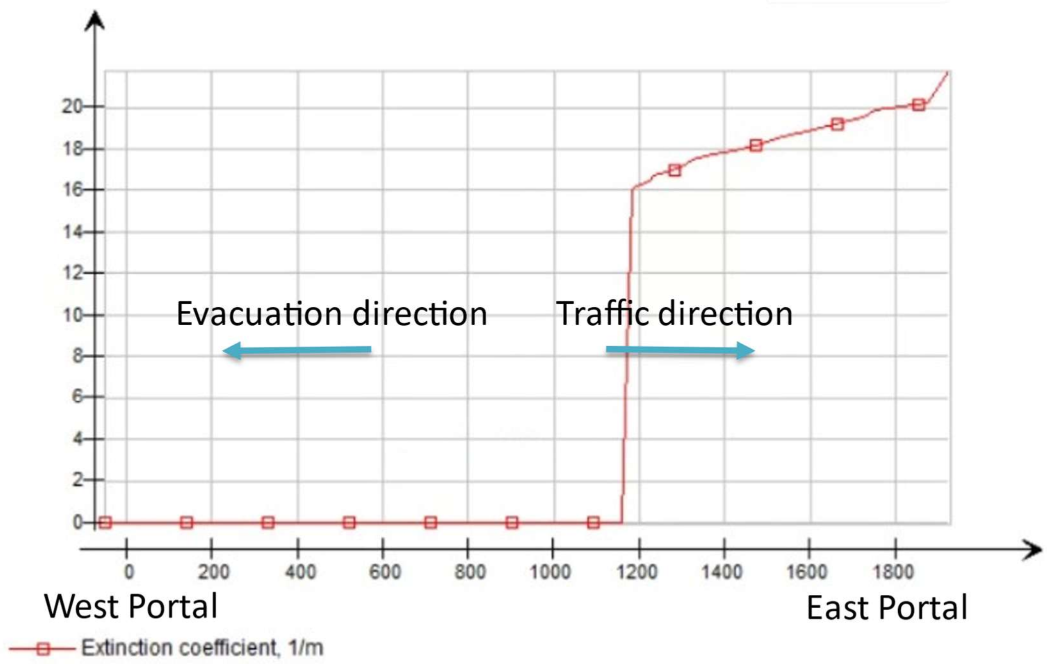
Air Temperature along the tunnel

Figure 41: Air Temperature for East Bound, Fotu la Tunnel – Mode 7

Smoke Extinction Level



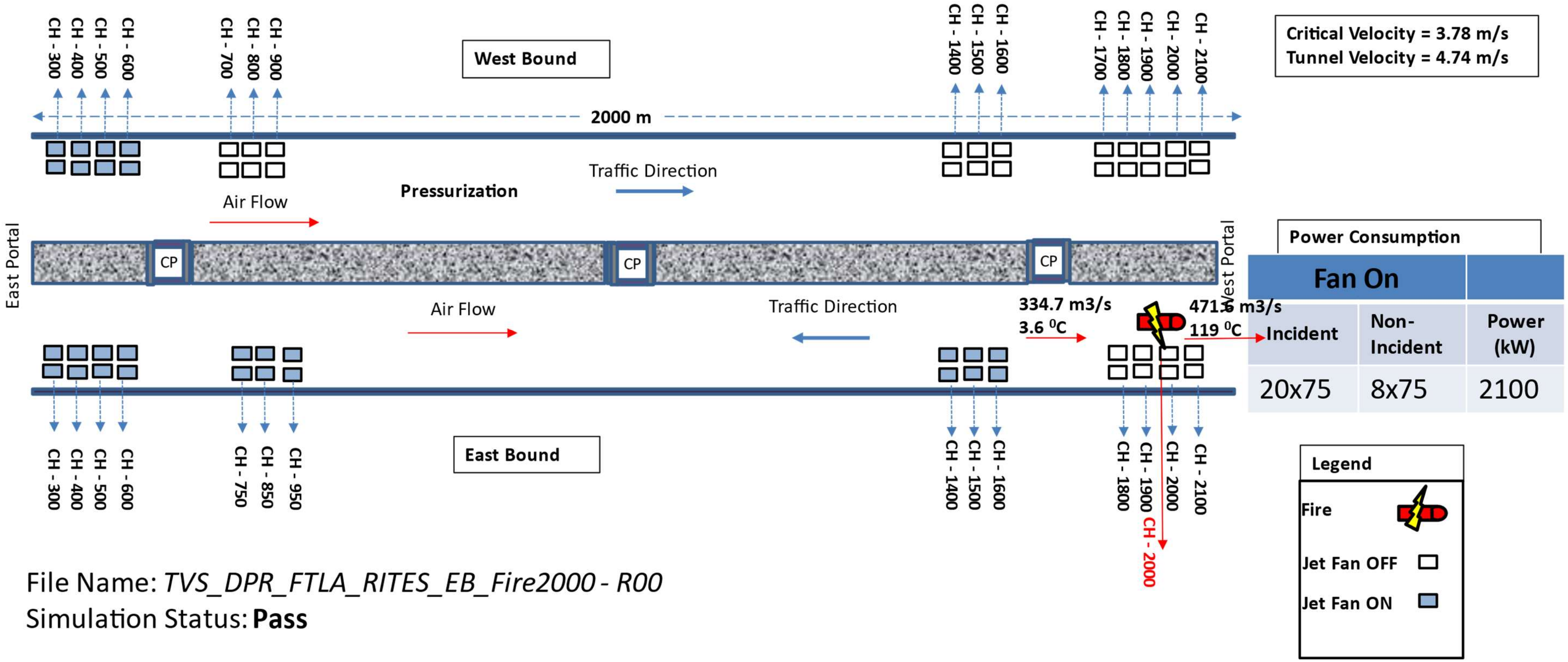
Contour plot



Smoke Extinction along the tunnel

Figure 42: Smoke Extinction for East Bound, Fotu la Tunnel – Mode 7

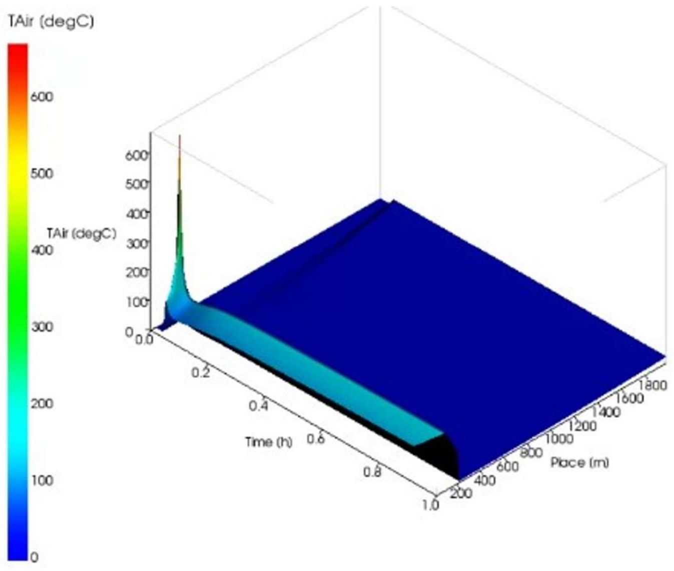
Emergency Mode – East Bound @CH:2000

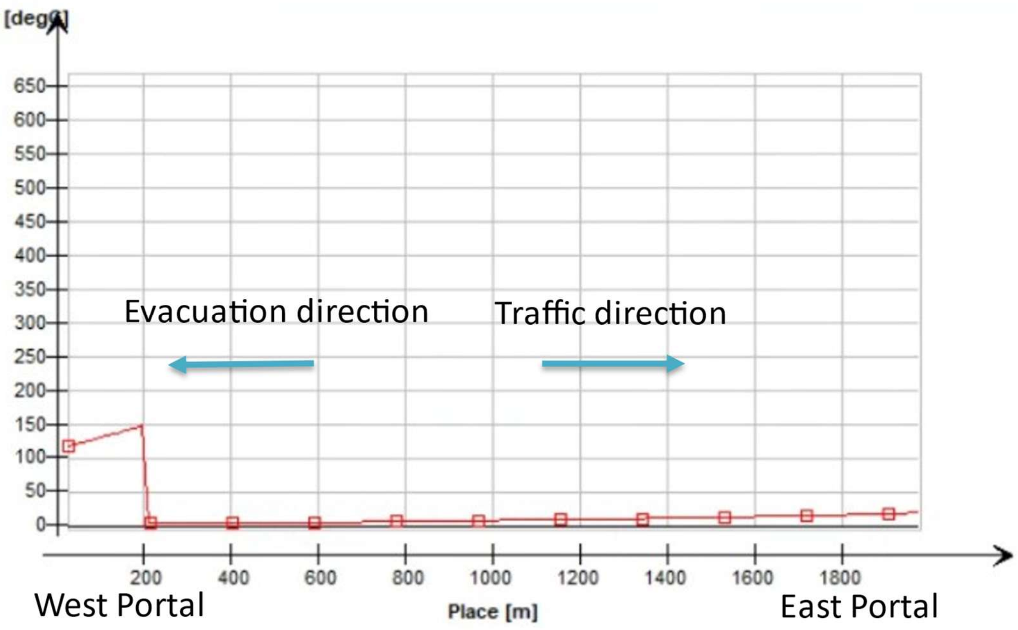


File Name: *TVS_DPR_FTLA_RITES_EB_Fire2000 - R00*
Simulation Status: **Pass**

Figure 43: Fotu La Tunnel Emergency Operation Mode for East Bound -Mode 8

Air Temperature



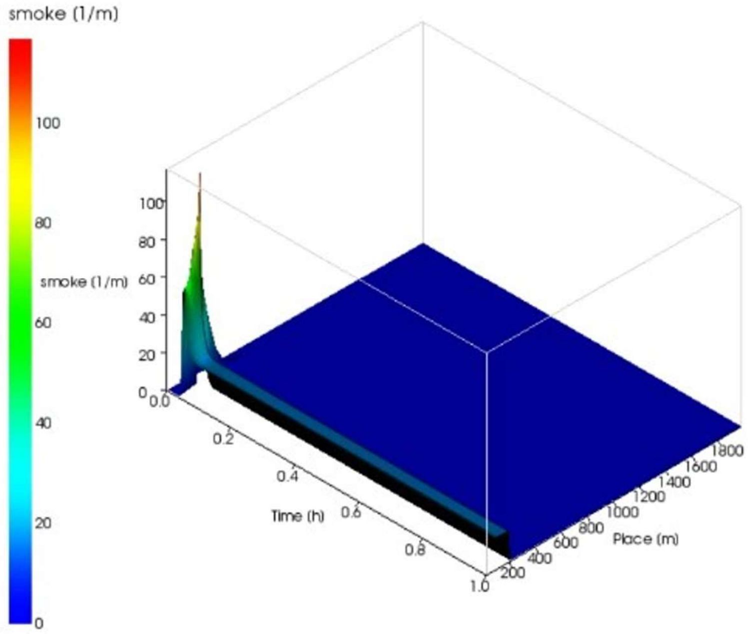


Contour plot

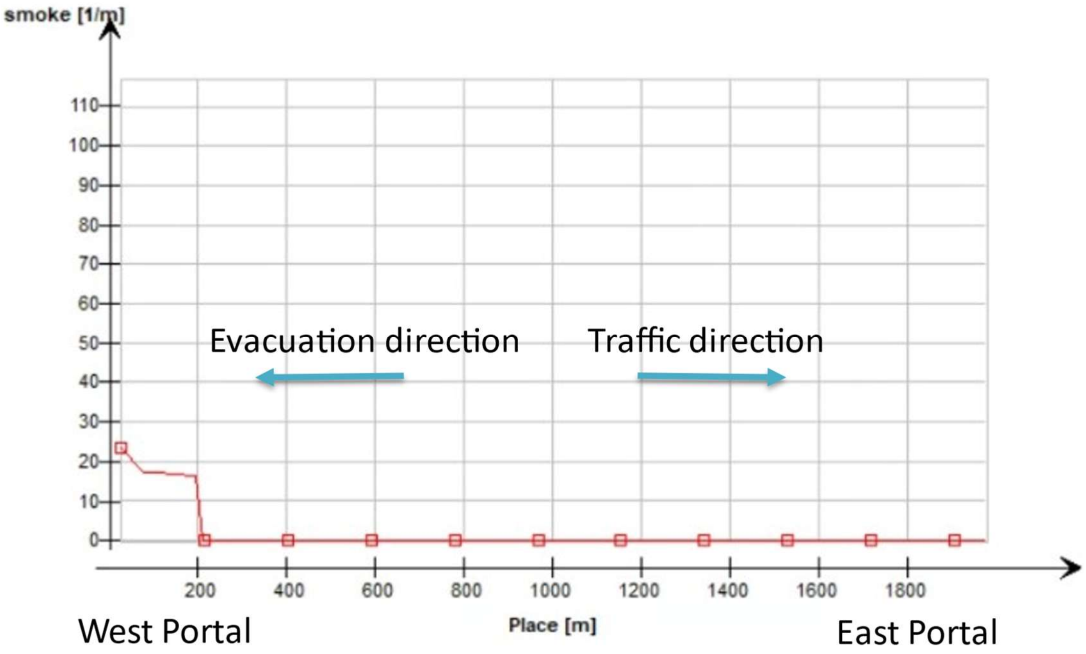
Air Temperature along the tunnel

Figure 44: Air Temperature for East Bound, Fotu la Tunnel – Mode 8

Smoke Extinction Level



Contour plot



Smoke Extinction along the tunnel

Figure 45: Smoke Extinction for East Bound, Fotu La Tunnel – Mode 8

15 APPENDIX IV – OPERATION MODE TABLE

Table 14: Operation Mode Table

Mode			Traffic flow direction	Jet Fan Location															Total Operating Fan in the tunnel	Operating kW
				CH-300	CH-400	CH-500	CH-600	CH-700[*]	CH-800[*]	CH-900[*]	CH-1400	CH-1500	CH-1600	CH-1700	CH-1800	CH-1900	CH-2000	CH-2100		
Normal	Mode 1-a		West Bound	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	0	0
	Mode 1-b		East Bound	OFF	OFF	OFF	OFF	OFF	OFF	--	OFF	OFF	OFF	--	OFF	OFF	OFF	OFF	0	0
Congestion	Mode 2-a		West Bound	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	0	0
	Mode 2-b		East Bound	OFF	OFF	OFF	OFF	OFF	OFF	--	OFF	OFF	OFF	--	OFF	ON	ON	ON	6	450
Emergency	Mode 3	CH:300	West Bound	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	24	2100
			East Bound	OFF	OFF	OFF	OFF	OFF	OFF	--	OFF	OFF	OFF	--	OFF	OFF	ON	ON	4	
	Mode 4	CH:1000	West Bound	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	ON	ON	ON	ON	28	2400
			East Bound	ON	ON	OFF	OFF	OFF	OFF	--	OFF	OFF	OFF	--	OFF	OFF	OFF	OFF	4	
	Mode 5	CH:2000	West Bound	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	ON	ON	ON	ON	OFF	OFF	22	2700
			East Bound	ON	ON	ON	ON	ON	ON	--	OFF	OFF	ON	--	OFF	OFF	OFF	OFF	14	
	Mode 6	CH:300	West Bound	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	OFF	ON	OFF	ON	ON	ON	ON	12	2700
			East Bound	OFF	ON	ON	ON	ON	ON	--	ON	ON	ON	--	ON	ON	ON	ON	24	
	Mode 7	CH:1000	West Bound	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	OFF	ON	OFF	OFF	OFF	ON	ON	8	2550
			East Bound	ON	ON	ON	ON	ON	ON	--	ON	ON	ON	--	ON	ON	ON	ON	26	
	Mode 8	CH:2000	West Bound	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	8	2100
			East Bound	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	--	OFF	OFF	OFF	OFF	20	

Note [*]: For East Bound the fan locations are at 750, 850 and 950 instead of 700, 800 and 900.

16 STANDARDS AND DOCUMENTS REFERENCE

To define and establish the criteria for ventilation system design, following documents have been taken as a reference:

1. **IRC**: SP:91-2019 - Guidelines for Road Tunnels, Indian Road Congress.
2. IRC: SP:84: 2014- Manual for Specifications and Standards for Expressways for Four Laning of Highways.
3. Report 2019R02EN - World Road Congress PIARC, Road Tunnels: Vehicle Emissions and Air Demand for Ventilation.
4. Report 05.05.B, 1999 - World Road Congress PIARC, Road Tunnels: Ventilation for Fire and Smoke Control.
5. NFPA 502:2017 - Standard for Road Tunnels, Bridges and Other Limited Access Highways.
6. NFPA 502:2020 - Standard for Road Tunnels, Bridges and Other Limited Access Highways.
7. NFPA 92 - Standard for Smoke Control Systems in Malls, Atria, and Large Spaces
8. BD 78/99 – Design of Road Tunnels
9. Bundesami fur Strassen; Richtliie Luftung der Strassentunnel, Systemwahl, Dimensionierung und Ausstattung V2.0, Ausgabe 2008 (Swiss Tunnel Ventilation Design Code)
10. CETU, Centre d'etudes des tunnels ; dossier pilote des tunnels equipment – section 4.1 – ventilation; Novervmbre 2003 (French Tunnel Ventilation Design Code)
11. World Road Congress PIARC, Systems and Equipment for fire and smoke control in road tunnels.
12. Pressure drop caused by a fire in a tunnel, P Carlotti, Pietro Salizzoni
13. On The Aerodynamics Of Water Mist from a Ventilation Designer's Perspective, I. Riess, M. Steck
14. ASHRAE Fundamentals - 2021
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