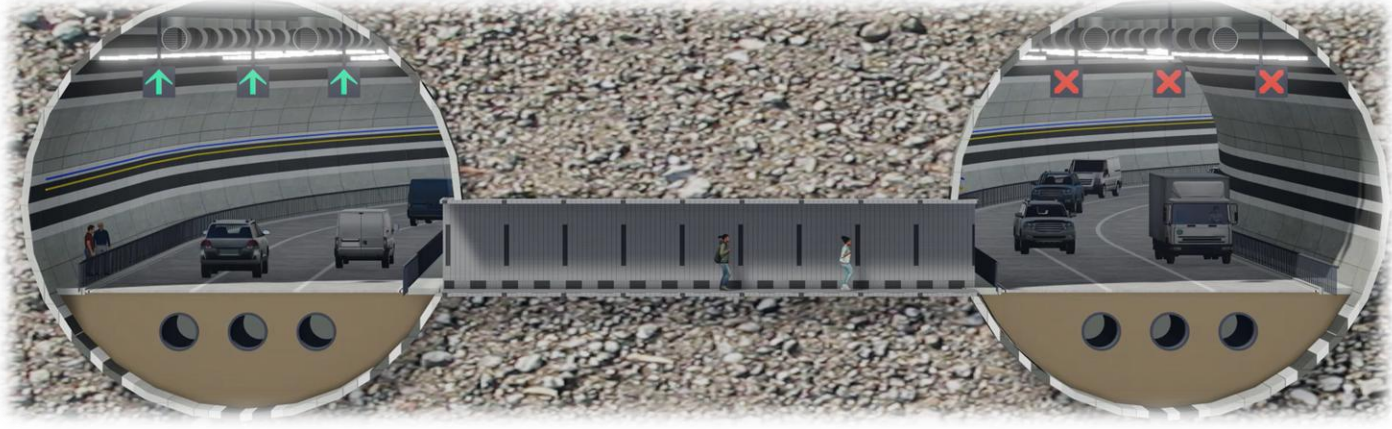
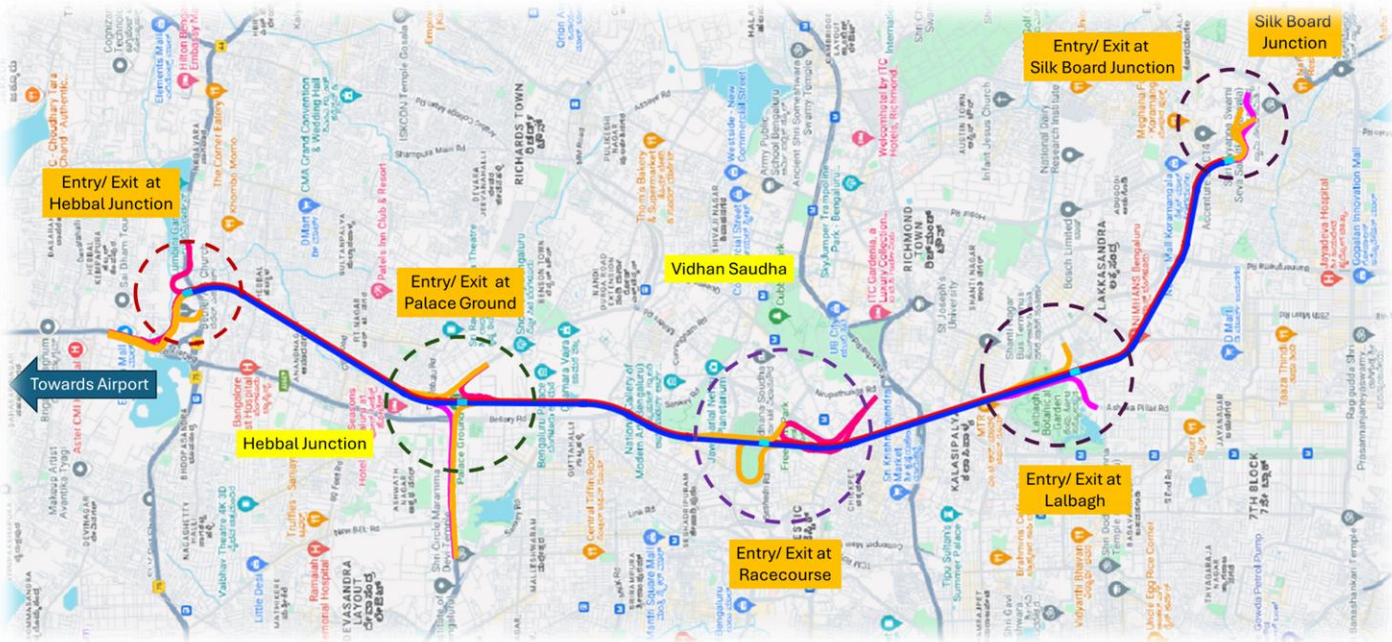




GOVERNMENT OF KARNATAKA



CONSULTANCY SERVICES FOR PREPARATION OF DPR FOR THE WORK OF CONSTRUCTION OF UNDERGROUND VEHICULAR TUNNEL FROM HEBBAL ESTEEM MALL JUNCTION TO SILK BOARD KSRP JUNCTION



FINAL DETAILED PROJECT REPORT

VOLUME - II D

VENTILATION DESIGN REPORT (R-I)

MAY 2025





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1 VENTILATION SYSTEM DESIGN

1.1 Introduction

Tunnel ventilation systems should provide adequate in-tunnel air quality during normal and congested traffic operations and support the self-evacuation and rescue efforts during emergency incidents. Separately, the tunnel ventilation capacity requirements for emergency ventilation (typically for the control of smoke and hot gases during fire) must also be assessed and the system designed accordingly. This document presents the design of the ventilation system for the proposed "Underground Vehicular Tunnel from Hebbal Esteem mall junction to Silk Board KSRP junction". Two ventilation scenarios will be considered:

- i) Ventilation during normal operation of the tunnel, and
- ii) Ventilation for a fire inside the tunnel.

The ventilation system is designed to provide:

1. The minimum air required to ensure adequate in-tunnel air quality and visibility thresholds during normal operation
2. A tunnel environment as safe as possible for the users and rescue services during a fire incident.

Following general factors are considered in the design:

1. Length of the tunnels (main tunnel and the entry and exit tunnels)
2. Cross section (width and height) of the tunnels.
3. Type of traffic
4. Fire safety
 - a. Presence of emergency exits
 - b. Change in the direction of fans
5. Cost and Environmental issues
 - a. Energy consumption
 - b. Localized and concentrated emission of polluted air from portals and stacks.

1.2 Design Process

Overall design process is as follows:

1. Divide the tunnel into different sections considering entry-exit ramps and sections between the ventilation stations.
2. For each section for normal operation of the tunnel:
 - a. Estimate the pollutant emission rate for congestion (maximum ventilation capacity). This is done by considering different speeds of 0 – 50 km/h.
 - b. Estimate the tunnel air flow rates and velocities for pollutant removal. Air flow rates for diluting CO, NO_x and PM are separately calculated and the maximum of the three flow rates is considered for further design of the ventilation system.
 - c. Estimate the tunnel pressure drop.
 - d. Calculate the number of fans and the distance between fans based on the pressure drop.
3. For each section for fire scenario:
 - a. Choose the fire curve and heat release rate
 - b. Estimate the tunnel air flow required for efficient smoke removal.
 - c. Check if the maximum capacity and the arrangement of the fans chosen based on pollutant dilution (normal operation) are sufficient to provide the air flow rate and pattern required for the

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smoke removal. If yes, choose between the two systems based on other constraints such as construction procedure, energy consumption and cost. If not, upgrade the fan power, number, positions and control to satisfy the smoke removal requirement.

- d. Decide the exhaust and intake locations and directions to avoid mixing of both the air streams in the nearby ambient.
- e. Decide the firefighting systems required.
 - i. Sensors
 - ii. Sprinklers
 - iii. Fire extinguishers
 - iv. Fire hoses
4. Prepare the list of items required and estimate the material and installation cost.
5. Prepare the guidelines for operation and maintenance: evacuation strategy, automatic control of fan power and directions, closing and opening of dampers, remote monitoring etc.
6. Do 3D simulations of selected regions to verify the ventilation system design both for normal and emergency (fire) scenarios.

1.3 Layout of the Proposed Tunnel

Proposed underground vehicular tunnel has two separate unidirectional tubes throughout between Esteem mall to Central silk board. Each tunnel has an inside diameter of 13.5 m. In addition, there are number of entry and exit tunnels. The layout of the tunnel is shown in following figure

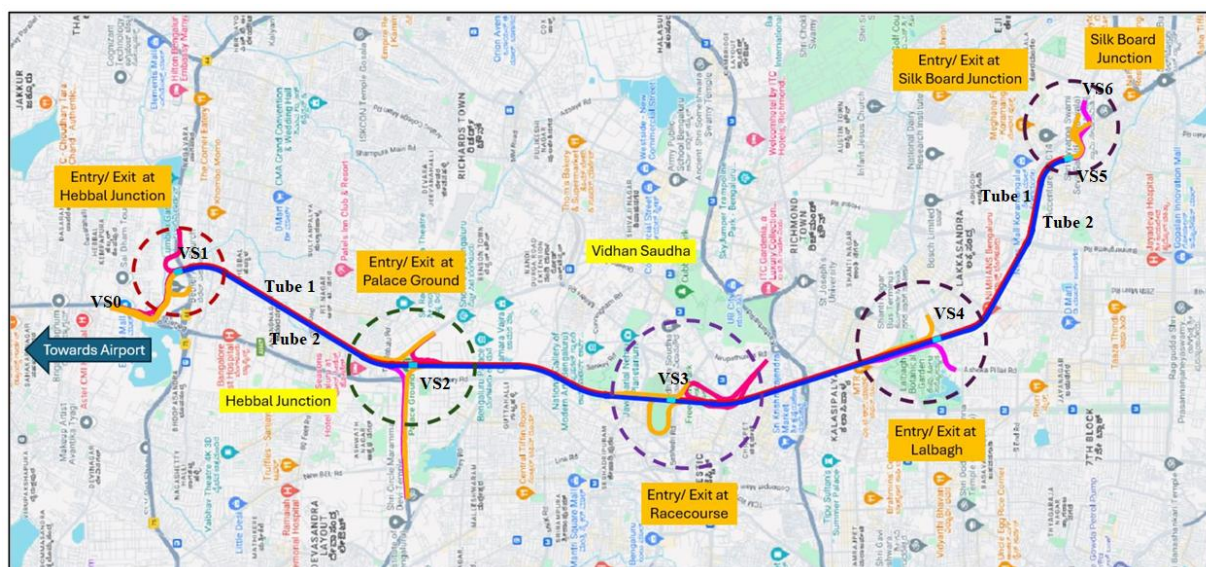


Figure 1: Layout of the proposed underground vehicular tunnel

The entire layout has been divided into North side and South side. The detail of the project packages are as mentioned below:

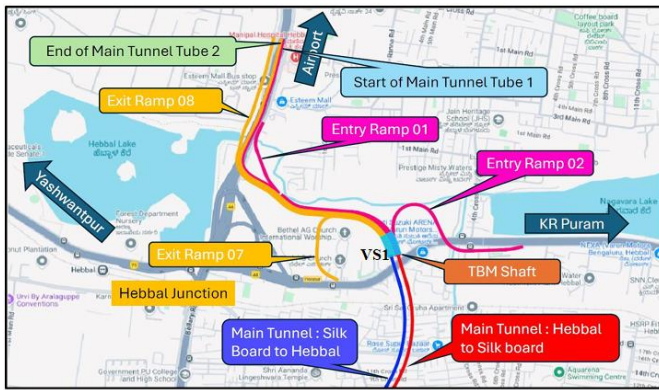
- Northern Package 1: Hebbal near Esteem Mall junction (Km. 0+000) to Seshadri Road, Freedom Park (Km 8.748).
- Southern Package-2 : From Seshadri Road, Freedom Park (Km 8.748) to Silk Board (Km 16.745)

The ventilation stations, entry ramps and exit ramps corresponding to these packages are shown in figure 2 and figure 3 below.

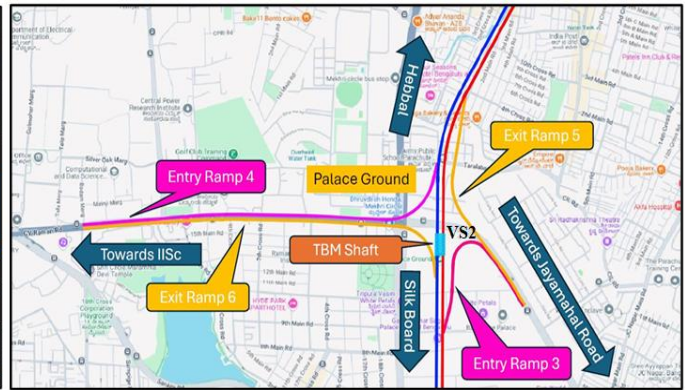


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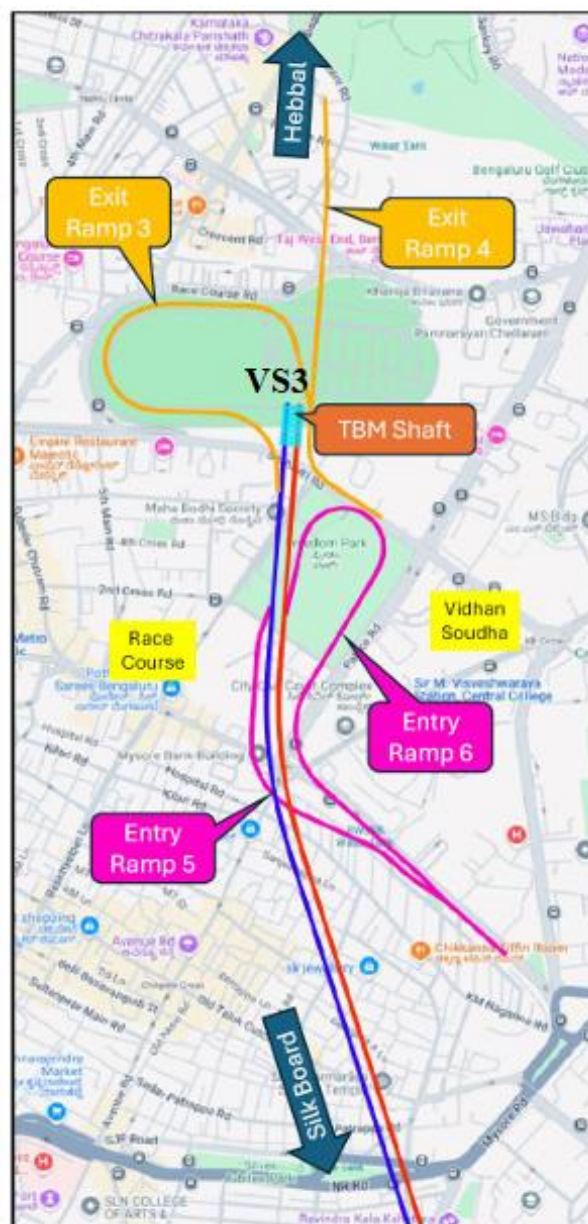


(a)



(b)

Figure 2: Entry and exit ramps alongside the ventilation stations for package 1, (a) Entry and exit ramps from Esteem mall Hebbal to Mekhri circle (palace ground) (b) Entry and exit ramps from Mekhri circle to Racecourse



(a)

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(b)

(c)

Figure 3: Entry and exit ramps alongside the ventilation stations for package 2, (a) Entry and exit ramps from Race course to Lalbagh (b) Entry and exit ramps from Racecourse to Lalbagh (c) Entry and exit ramps from Lalbagh to central silk board (CSB)

The locations of actual exits and entry points for both sides and ventilation stations are given in table 1 to table 4.

Table 1 : Entry and exit tunnels for the traffic from Esteem Mall to Central Silk Board

Name	Name (according to dwg file)	Entry/Exit	Distance from Esteem Mall, m	Length, m
Esteem Mall to Mekhri Circle	Entry Ramp 1	Entry	800	341
	Entry Ramp 2	Entry	1343	814
	Exit Ramp 5	Exit	4350	1110
Mekhri Circle to Race Course	Entry Ramp 3	Entry	5450	871
	Exit Ramp 4	Exit	7950	790
Race Course to Lalbagh	Entry Ramp 6	Entry	9250	1783
	Exit Ramp 2	Exit	11800	1081
Lalbagh to CSB	Exit Ramp 1	Exit	16400	455

Table 2 : Entry and exit point for the traffic from Central Silk Board to Esteem Mall

Name	Name (according to dwg file)	Entry/Exit	Distance from Esteem Mall, m	Length, m
Esteem Mall-Mekhri Circle	Exit Ramp 8	Exit	548	548
	Exit Ramp 7	Exit	1100	473
	Entry Ramp 4	Entry	4700	1945
Mekhri Circle-Race Course	Exit Ramp 6	Exit	5200	1942
Race Course-Lalbagh	Exit Ramp 3	Exit	9000	1465
	Entry Ramp 5	Entry	9250	1197
	Entry Ramp 7	Entry	11650	1416
Lalbagh -CSB	Entry Ramp 8	Entry	16400	654

Table 3 : Ventilation Sections (VS0 and VS6 are the main entry and exits):

Ventilation Sections	Distance from Esteem Mall to the farthest station, m	Length of section, m
VS0 - VS1	1400	-
VS1-VS2	5100	3570
VS2-VS3	8725	3625
VS3-VS4	12625	3820
VS4-VS5	15970	3258
VS5-VS6	16745 (Tube 1)	-
	16571 (Tube 2)	-



Table 4 : Entry and Exit ramps between Ventilation Stations (VS1 to VS5)

Ventilation Station Section	Number of Entries & Exit (Esteem Mall – CSB)	Number of Entries & Exit (CSB - Esteem Mall)
VS0 - VS1	2	2
VS1-VS2	1	1
VS2-VS3	2	1
VS3-VS4	2	3
VS4-VS5	0	0
VS5-VS6	1	1

Figure 4 shows the schematic of the tunnel system, derived from the layout shown in figure 1, from the ventilation point of view.

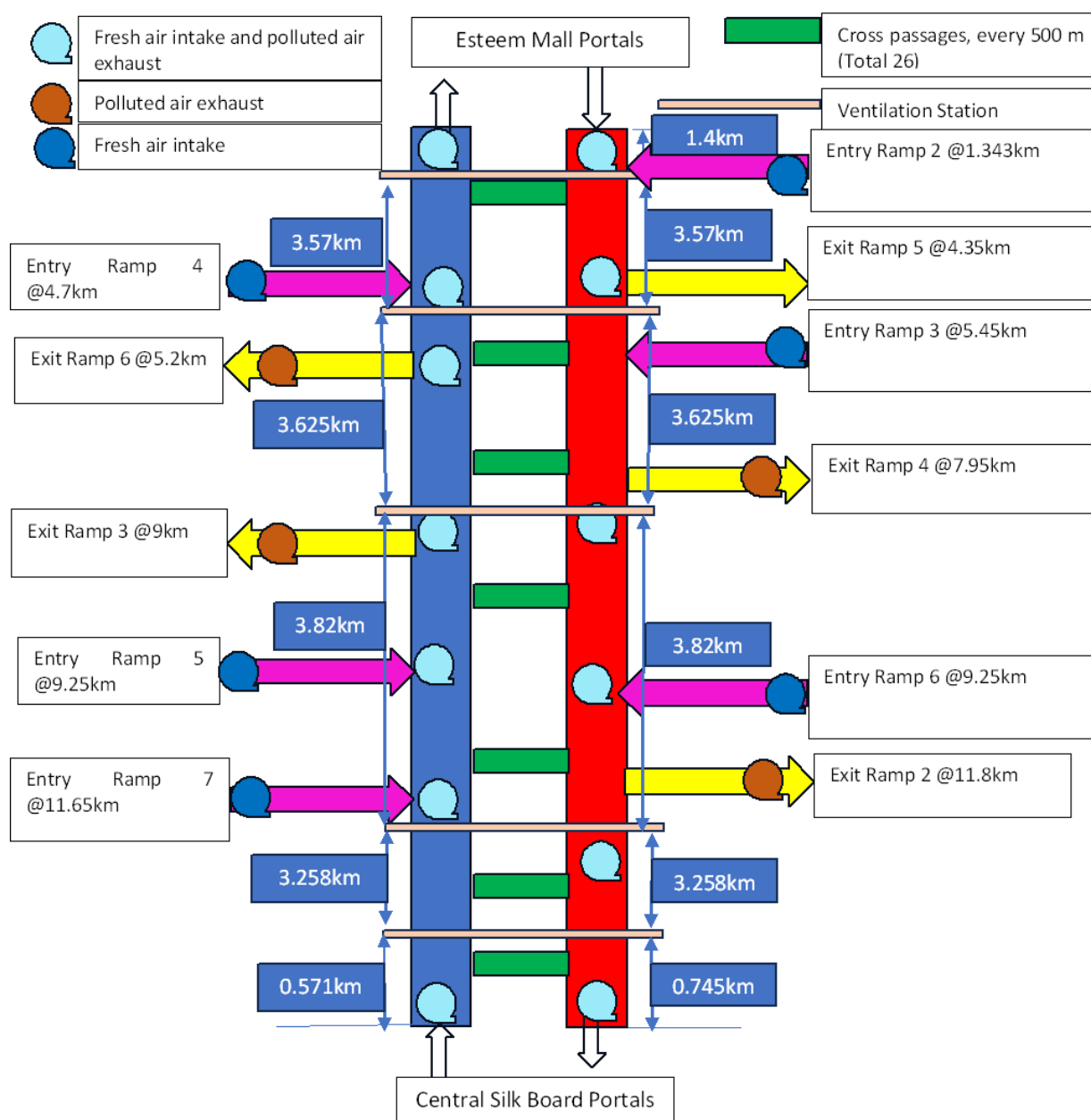


Figure 4: Schematic of the general layout of the proposed tunnel with Ventilation Stations (not to the scale)

The Portion between two consecutive ventilation stations and the entry and exit ramps are considered as the sections. Fresh air intake and polluted air exhaust are placed only at the ventilation stations.



1.4 Tunnel Cross Section

Figure 5 shows the tunnel cross-section of the tubes. Inside diameter is 13.5 m. Vehicle clearance is 5.5 m. Free space available is 3.22 m, out of which 0.5 m is required for signs. The pavement is 2.6 m below the centre. Each lane is 3.5 m. The cross-section area is 105 m².

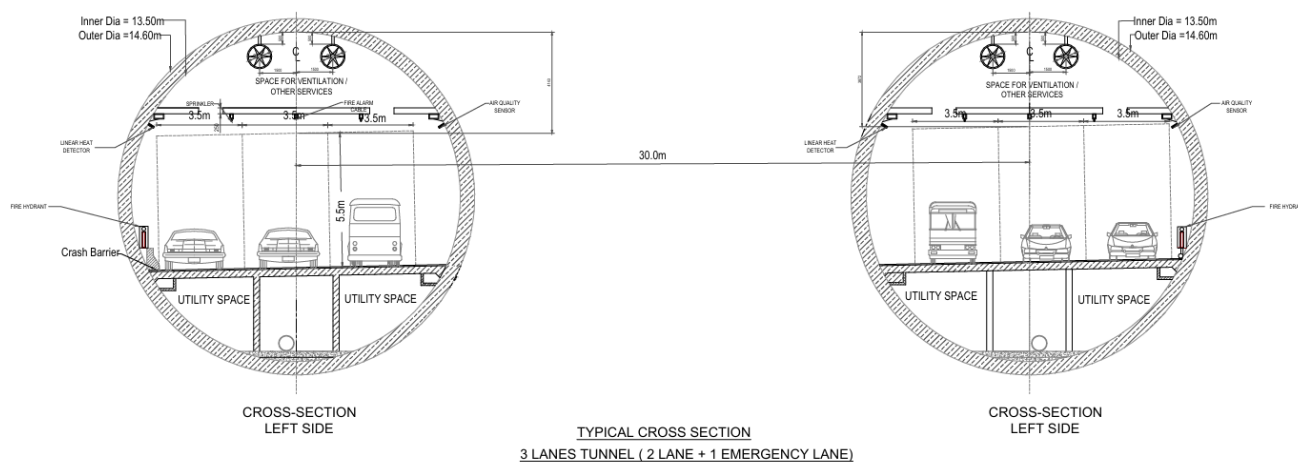


Figure 5: Tunnel cross-section

1.5 Design of a Ventilation System

The design of ventilation system is discussed with respect to two main elements, the type of ventilation and dimensioning and positioning of ventilation system type selected

1.5.1 Ventilation System type

There are mainly two types of ventilation systems exist:

1. Natural ventilation:
2. Mechanical ventilation

The guidelines provided in “IRC_SP 91-2019” section 5.2 suggests that the mechanical ventilation system is required for the tunnel lengths/section lengths more than 500 m. As per the Table 1 to 3 data, the different tunnel sections proposed for ventilation system design have length larger than 500 m. Therefore, the mechanical ventilation system will be considered for the design. This ventilation systems mainly are of two types (Figure 6):

- 1) Longitudinal: This is the simplest tunnel ventilation system, and the most used nowadays, and it consist mainly in developing an air flow inside the tunnel by means of jet-fans or Saccardo nozzles, so that fresh air comes in at one side and polluted air / smoke goes out through the other end of the tunnel. According to IRC_SP91-2019 section 5.2, this system is suitable to use for the tunnel lengths of 500 m to 4000 m with light traffic density. However, this system needs to be provided with intermediate shafts for massing exchange of exhaust with fresh air.
- 2) Transverse:
 - Fully transverse: A fully transverse system consists in 2 different ducted ventilation systems, one for fresh air injection (preferable at floor level) and another for exhaust (at the ceiling), evenly distributed along the tunnel. This system is the best for contaminants control. Its main disadvantage is the high cost involved due to the complex and large civil infrastructures needed (shafts, ventilation buildings, ducts). However, practically there is no limit to the tunnel length to use this system. For the longer tunnel lengths with heavy traffic, this system is suitable.
 - Semi transverse: In this case there is only a ventilation duct along the tunnel that can work either injecting fresh air for contamination control or exhausting smoke in a similar way as a transverse system. This system needs to be provided with intermediate shafts for massing exchange of exhaust with fresh air more frequent than fully transverse system. As per IRC_SP-91, 2019 section 5.2, the semi-transverse systems are required to have shafts installed at every 3 km.



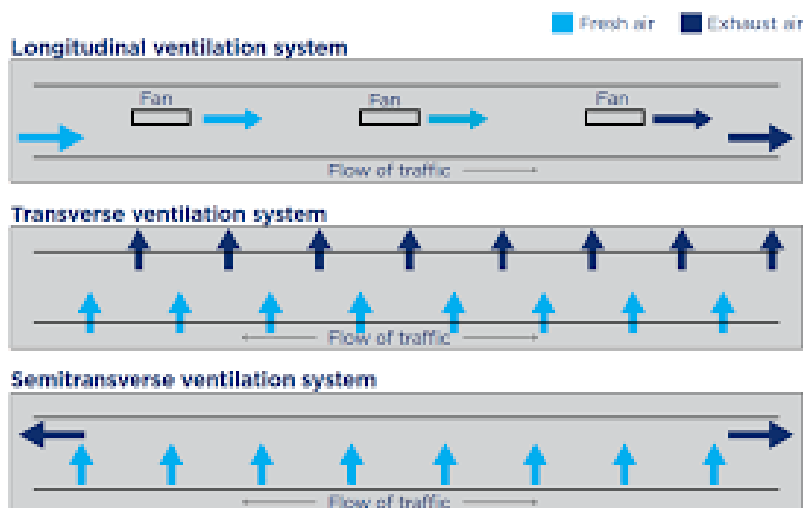


Figure 6: Schematic of different types of ventilation systems

Figure 7 shows an example of ventilation system selection process.

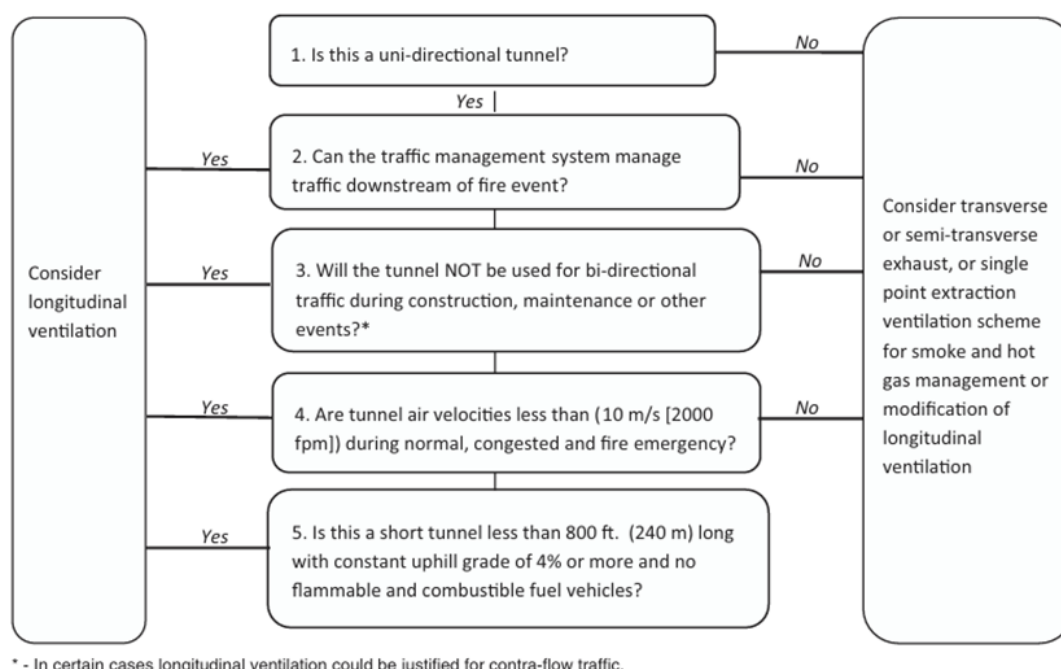


Figure 7: An example of ventilation system selection process (Maevski, 2017)

These ventilation types include three main types of fans, namely axial, propeller and centrifugal. The selection of the types of ventilation system and its equipment's will be decided based on the fresh air demand and the lengths of each section.

1.6 Choice of the Ventilation System

In order to select the suitable type of the ventilation system for the particular section, the lengths of the sections given in table 1 to 3 are analysed and the general discussion provided in the previous section about ventilation system types is considered for the same. Table 5 contains the general characteristics of the proposed tunnel.

Table 5 : Tunnel General Characteristics

Factor	Remarks
Length of the tunnel	Four tunnel sections between ventilation shafts with lengths ranging from 3.26 km to 3.8 km





Factor	Remarks
	Different entry and exit ramps with lengths more than 500 m
Possibility of congestion	Yes, Heavy traffic expected in main tubes
Traffic type (bidirectional or unidirectional)	Two unidirectional tubes interconnected through cross passages
Type of vehicles	PCU and electric buses
Possibility of fire	Yes

Based on the details given table above and as per the guidelines provided in previous section, the entry and exit ramps with lengths more than 500 m are proposed to have longitudinal systems. In these sections, the air flow under normal operating conditions will be in the direction of traffic.

Main tunnels with sections between the ventilation stations will have a fully transverse system due to the length of the sections (IRC_SP-91, 2019). The fresh air injection and extraction will be carried out at the ventilation shafts at the ventilation stations.

Hence, the complete system is a combination of longitudinal and fully transverse systems. This choice of ventilation system remains same based on fire smoke extraction point of view.

The main tunnels will be connected through cross passages at an interval of 500 m for air flow as well as vehicles and people in a fire event (Item 8 in Annexure B of IRC-SP91, 2019; Note 2 in Section 2.8.2.5 of IRC-SP91, 2010). These passages are also installed with longitudinal ventilation system.

These details are given in following table.

Table 6 : Choice of ventilation system for the proposed vehicular tunnel

Sections	Type of ventilation system
Entry and exit ramps with lengths more than 500 m and cross passages	Longitudinal
Main tube sections between ventilation stations	Fully transverse

It is important to note that, the consideration of the longitudinal and semi-transverse ventilation system for the main tube sections is ruled out due to section lengths as longitudinal system is suitable for these sections with light traffic density (which is not the case) and semi-transverse system needs the shafts installed at every 3 km.

The design calculations to estimate the fresh air flow requirement and the number of fans for both normal operation and for fire scenario for these sections are discussed hereafter in next sections.

1.7 Ventilation during normal operation of the tunnel

The proposed methodology for ventilation system design during normal operation of the tunnel consists of the following four steps.

- 1) Estimation of pollutant load
- 2) Estimation of fresh air requirement
- 3) Design of Ventilation system
- 4) Computational analysis to verify the designed system

1.7.1 Estimation of Pollutant Load

As per PIARC guidelines, the emissions in terms of CO, NO_x (sum of NO and NO₂) and particulate matters (PM) are considered as the pollutant load resulting from the IC engine driven vehicles for road tunnel ventilation system design. The calculation of the quantity of toxic pollutants produced in the tunnel according to a specific traffic scenario is based on reference emission rates multiplied by influencing factors and the number of vehicles, as described in this section. The resulting 'total emission rate' is then used to determine the fresh-air demand.

The estimation of total emission rate or pollutant load inside the underground tunnel will be based on following considerations:

- 1) Analysis of alignment to decide sections





2) Analysis of traffic flux: vehicle categories and number of vehicles.

1.7.2 Analysis of Alignment to Decide Sections

At first, the underground road topology will be surveyed based on the geographic data, cross sections of the tunnel at different locations, vertical profiles (road gradients).

Then as per the guidelines provided in the section 5 of the PIARC Report: “Road Tunnels: Vehicle Emissions and Air Demand for Ventilation”, 2019, the complete length of the tunnel is divided into different sections based on constant cross section and gradient, altitude, traffic density, entry and exit portals and anticipated restrictions on exhaust emission locations.

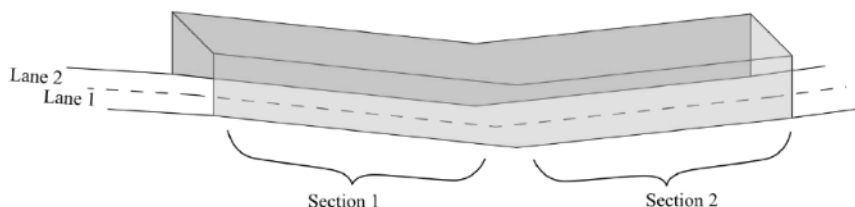


Figure 8: Schematic of sections selected based on constant slope/gradient

Individual sections are selected based on the ventilation station location details given in Section 0.

1.7.3 Analysis of Traffic Flux: Vehicle Categories and Number of Vehicles

As per the PIARC guidelines, the road vehicles are categorised in terms of their function and size as follows:

- Passenger car (PC)
- Light commercial vehicle (LCV)
- Heavy goods vehicle (HGV)

The HGV category consists of the vehicles which are having size over 3.5 tons. These include trucks, articulated lorries, buses and coaches.

These vehicle categories can be sub-categorized by fuel, e.g. gasoline (petrol) or diesel such as:

- PC Gasoline
- PC Diesel
- LCV Gasoline
- LCV Diesel
- HGV Diesel

The emission data corresponding to these vehicle types for the year 2018 is available in the PIARC which will be used as a base emission data. HGV emissions are also highly dependent on vehicle mass and a mass factor will be applied to account for this as per PIARC guidelines. For the estimation of emission rate from each vehicle type, the information about the number of vehicles of each type in traffic flux is required to be known.

Summarizing the details discussed in the two parts of this section, the following input parameters will be considered for the estimation of pollutant load in terms of emission rates for each section of the tunnel:

- Length of the tunnel/section
- Road gradient or slope
- Tunnel altitude
- No. of different types of vehicles passing through the tunnel per hour. The vehicles mainly include; passenger car units (PCU), light commercial vehicle (LCV), heavy commercial vehicle (HCV), heavy goods vehicle (HGV), electric vehicles (EV)

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- Speed of the vehicles. The speed of the vehicles will be different for different traffic conditions, normal and congested ones.
- Parameter influencing the power needed to propel the vehicle such as average mass of the HGV vehicle
- Pollutant concentration in fresh air/ fresh air quality separate estimations will be provided for the CO and NO_x and to the particulate matter by appropriately taking into account the reduction factors provided in the reference documents to bridge the gap between available data and future years estimation requirements. Figure 9 shows a sample emission rate for petrol passenger cars as a function of speed and gradient (Ref: Vehicle Emissions and Air Demand for Ventilation, PIARC Report 2019R02EN)

v [km/h]	PC Gasoline CO [g/h] 2018						
	Gradient [%]						
	-6	-4	-2	0	2	4	6
0	5.4	5.4	5.4	5.4	5.4	5.4	5.4
10	7.7	8.8	9.7	11.0	12.0	14.1	16.6
20	8.4	10.2	12.6	15.5	22.7	35.4	50.2
30	7.7	9.3	11.1	13.7	17.3	22.8	31.1
40	8.3	10.3	12.9	16.4	22.3	33.2	48.9
50	8.9	11.8	14.0	18.2	23.8	33.1	46.7
60	8.5	11.4	13.3	18.2	25.3	37.8	59.2
70	9.9	13.3	17.9	25.6	36.4	60.4	109.0
80	12.5	16.2	21.1	31.0	49.8	89.1	166.2
90	11.7	15.7	22.7	35.6	67.5	146.1	264.3
100	15.5	20.9	31.6	50.4	85.9	209.4	415.7
110	26.7	33.2	47.4	78.1	148.6	326.2	791.2
120	47.2	54.9	74.1	130.7	259.8	604.4	1506.2
130	85.3	106.2	142.2	236.6	504.3	1318.7	2568.7

Figure 9: Typical emission rate data

For the present design, based on the information received from the traffic analysis, the vehicle composition is 100 % PCUs from ventilation system point of view. All are considered to be the petrol vehicles.

The emission data in figure 9 represents the estimations corresponding to year 2018 and time factors are used to relate to year 2025 (which are used in the calculation). These are based on the base emission rates provided in the PIARC report, Road Tunnels Vehicle Emissions and Air Demand for Ventilation_2019, section 6.1

1.7.4 Estimation of Pollutant Emission Rates

The pollutants considered are CO, NO_x and PM. The emission rates are considered for the two congestion scenarios:

1. Tunnel filled with stationary vehicles
2. Vehicles moving at speeds from 10 km/h to 50 km/h.

The number of vehicles decreases as speed increases. Therefore, considering the figure 9, the maximum emission rates are obtained at 40 km/h for the above-mentioned scenarios and are selected for further airflow rate requirement calculations. It is important to note that, the present design calculations are done for 0 % road gradient condition.

All the vehicles are petrol PCUs. Table 7 and 8 gives the emission rates estimated for all the sections. These emissions are estimated for the capacity of 12000 vehicles/h per section, based on the 40 km/h. This covers the maximum possible emission and associated traffic influx.

Table 7 : Emission rates (g/h and m²/h) in different sections between ventilation stations for one tunnel (VS1 to VS5 are ventilation stations)

Section	Section length (m)	Highest emission rate from different speeds		
		CO (g/h)	NO _x (g/h)	PM (m ² /h)
VS1-VS2	3570	13700	2058	203
VS2-VS3	3625	13911	2090	207
VS3-VS4	3820	14660	2203	218
VS4-VS5	3258	12503	1879	186





Table 8 : Emission rates (g/h and m²/h) in different entry and exit ramp sections

Section	Section length (m)	Highest emission rate from different speeds		
		CO (g/h)	NO _x (g/h)	PM (m ² /h)
Entry ramp 2	674	1724	259	26
Exit ramp 5	820	2098	315	31
Entry ramp 3	581	1486	223	22
Exit ramp 4	790	2021	304	30
Entry ramp 6	1621	4147	623	62
Exit ramp 2	960	2456	369	36
Entry ramp 4	1615	4132	621	61
Exit ramp 6	1612	4124	620	61
Exit ramp 3	1465	3748	563	56
Entry ramp 5	1035	2648	398	39
Entry ramp 7	1286	3290	494	49

It is important to note that, the actual lengths of these entry and exit ramps are different. The section length given in table indicate the only lengths over which ventilation system is designed.

1.7.5 Estimation of Fresh Air Requirement

The fresh air requirement is estimated in reference to design and operational pollutant values, therefore this section is sub divided into two:

- 1) Design (threshold) and operational pollutant values
- 2) Fresh air requirement estimation

1.7.5.1 Design (threshold) and Operational Pollutant values

Design values provide a basis for the determination of the required capacity of the tunnel ventilation system. Operational values provide the limit levels for the different operating states such as normal operations, maintenance operations and closure conditions. PIARC 2019R02EN provided these values for different pollutants which will be considered are same are given as follows

- Design values for CO emission:

Table 9 : Design values for CO emissions, (IRC SP 91:2019, PIARC 2019R02EN)

Traffic situation	Design value	Operation condition	Operation limits
Free flowing peak traffic, 50 – 100 km/h	70 ppm	Normal operation	< 100 ppm
Daily congested traffic, stopped on all lanes	70 ppm	Planned maintenance work in a tunnel under traffic	20 ppm
Exceptional congested traffic, stopped on all lanes	90 ppm (100 ppm for IRC SP 91:2019)	Threshold value for tunnel closure	200 ppm

- Design values for NO_x:

NO by itself is not considered a harmful pollutant at commonly encountered levels. On the other hand, NO₂ is noxious and can irritate the lungs and lower the resistance to respiratory infections such as influenza. PIARC proposed to permit an average in-tunnel concentration of 1.0 ppm NO₂ along the length of the tunnel at any one time as the design value.

- Design values for particulate matter (PM):

The presence of particulates leads to reduced visibility inside the tunnel. Therefore, visibility criteria are intended to support the ability of a driver to stop safely. The tunnel ventilation system must provide visibility levels that exceed the minimum vehicle stopping distance at the design speed.

There are two primary sources of PM in a tunnel, exhaust emissions and non-exhaust emissions. Exhaust emissions consist of PM emanating from the tailpipe as a result of fuel combustion. Non-exhaust PM consists of tyre and brake wear, road surface abrasion and re-suspended dust.





Table 10 : Design values for visibility based on PM emissions, PIARC 2019R02EN

Visibility condition	Extinction coefficient K	Length of light beam L with $\frac{1}{I_0} e^{(-KL)} = 20\%$
Slightly hazy	0.003 m ⁻¹	536 m
Hazy	0.007 m ⁻¹	230 m
Foggy	0.009 m ⁻¹	179 m
Uncomfortable	0.012 m ⁻¹	134 m

1.7.5.2 Fresh Air Estimation

Once the pollutant load is estimated the fresh air requirement is estimated for the section considered based on the comparison of quality of polluted air to the admissible quality of air inside the tunnel (discussed in previous section) (IRC SP 91-2019, PIARC 2019R02EN).

The separate estimation of fresh air requirement (m³/h) will be provided based on estimated CO, NOx and PM loads in tables 6 and 7. The following input parameters will be considered in the calculations

- Total emissions from the vehicles (CO or NOx) in g/h, PM in 1/m
- Admissible pollutant level inside the tunnel (either CO or NOx) in g/m³, PM in 1/m
- Atmospheric air quality (either CO or NOx) in g/m³, PM in 1/m

The maximum of the air flow rate values obtained related to CO, NOx or PM emissions, will be considered in the design.

1.7.5.3 Tunnel air quality and visibility measurement system: recommendations

1. The operational ventilation inside the tunnel shall be managed by monitoring the tunnel air quality. This shall be managed through the tunnel measurement system which consists of measurement of visibility affected by dusty environment, measurement of CO and NOx emissions, flow velocity and direction measurement and temperature measurement etc.
2. The visibility sensors shall comprise of transmitter (TX) and receiver (RX) which work on the principle of a single pass light transmission system also known as optical measurement principle. The TX emits a visible (green) optical beam which is received by the RX. Any dust or smoke particles present will attenuate the light beam and cause the intensity of the light received by the RX to fall. This reduction in light intensity is used to determine visibility in the tunnel. The visibility criterion is mentioned in the normal operations above.
3. The tunnel air quality shall be monitored through the electrochemical cell technology to determine CO, NO & NO2 concentrations.
4. The ultrasonic airflow measurement technology shall be used in tunnels to measure the air flow velocity and direction. With no moving parts, the system requires minimal servicing and can be fully sealed from the tunnel's harsh environment. Measurements are independent of temperature, pressure and composition of the tunnel atmosphere. Other than a regular clean and check, it can be considered a 'fit and forget' solution. The two transducers shall be installed on the both walls of the tunnel in an angle of 45° to driving direction and shall work as sender and receiver alternately to determine the air flow speed and direction.
5. These sensors shall be positioned on the tunnel walls in equal distances to each other. The distance between air quality and visibility sensors shall be two times than the distance between the two air quality sensors and three times for air velocity and direction measurement sensors.
6. This system shall be connected to SCADA system through PLC and sensor measurements shall be provided through UPS.
7. 2 units of meteorological detection system shall be provided at the main entries of the two tunnel tubes which as per our understanding is sufficient.

1.7.6 Fresh Air Rate Requirements

Based on the pollutant emission rate obtained for parameters given in Table 7 and 8, the fresh air rate





required for each pollutant is calculated according to PIARC (2019R02EN) guidelines. These values are given in Table 11 and 12.

Table 11 : Fresh air rates (m³/s) required to dilute the pollutants in different sections between ventilation stations for one tunnel (VS1 to VS5 are ventilation stations)

Section	Section length (m)	Fresh air demand: highest airflow rate (m ³ /s)		
		CO	NO _x	PM
VS1-VS2	3570	39	304	11
VS2-VS3	3625	39	309	12
VS3-VS4	3820	42	325	12
VS4-VS5	3258	35	278	10

Table 12 : Fresh air rates (m³/s) required to dilute the pollutants in different entry and exit ramp sections

Section	Section length (m)	Fresh air demand: highest airflow rate (m ³ /s)		
		CO	NO _x	PM
Entry ramp 2	674	5	38	1
Exit ramp 5	820	6	47	2
Entry ramp 3	581	4	33	1
Exit ramp 4	790	6	45	2
Entry ramp 6	1621	12	92	3
Exit ramp 2	960	7	54	2
Entry ramp 4	1615	12	92	3
Exit ramp 6	1612	12	92	3
Exit ramp 3	1465	11	83	3
Entry ramp 5	1035	8	59	2
Entry ramp 7	1286	9	73	3

Based on table 11 and 12, amongst all the sections considered, the maximum fresh air rate of 325 m³/s is required for NO_x. So, this is chosen to estimate the pressure drop in the tunnel and decide the number of fans (both for longitudinal and fully transverse system) based on conservative approach for all the sections. The tunnel air velocity corresponding to this rate is 3.2 m/s in main tube sections, which is much less than the admissible longitudinal velocity of 10 m/s (PIARC, 1995) for long tunnels and more than the minimum air velocity range of 1-1.5 m/s recommended by IRC (Section 5.7 in IRC, 2019).

1.7.7 Ventilation System Fan Requirement

Number, flowrate and power of fans for different sections are calculated. The shortest spacing of the fans is recommended for the whole system.

1.7.7.1 Longitudinal System

Although, the longitudinal system is not used in the main tunnel sections between ventilation stations, these sections lengths are considered only to estimate the minimum distance between the fans based on conservative approach. Table 13 shows the input parameters used in the calculation of number of fans, minimum distance between them, and total power requirement for longest section. Table 14 gives the design values arrived at using the highest air flow requirement for all the sections per tube and the estimation of the number of fans for all the sections, for longitudinal system (Ref: PIARC, 1995). The distances of the sections VS1 to VS4 given in the table correspond to the distance between the two shafts.

Table 13 : Design values for a longitudinal system for the longest section, 3.82 km

Parameter	Value	Remarks
Tunnel cross section area, m ²	105	
Area available for air flow, m ²	92	Subtracting the vehicle cross section area
Fresh air rate, m ³ /s	325	For NO _x
Pressure drop in Tunnel, Pa	183	
Fan flow rate, m ³ /h	65000	
Fan area, m ²	0.79	

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Parameter	Value	Remarks
Pressure rise by fan, Pa	2.8	For the tunnel cross-section area
Total number of fans	65	
Distance between fans, m	118	Assuming two fans at one section
Type of fan	Traditional jet fan	
Power, kW	11.9	Per fan (minimum - estimated)

The pressure drop is calculated based on PIARC report 05-02-B.

Table 14 : Longitudinal System calculations for fan Requirements, all sections

Section	Section Distance (m)	Total NO _x Emission (g/h)	Air Flow Rate (m ³ /s)	Pressure Drop in tunnel, pa	No. of Fans	Total Power (kw)	Distance b/w Fans (m)
VS1-VS2	3570	2058	304	150	53	636	135
VS2-VS3	3625	2090	309	157	55	660	132
VS3-VS4	3820	2203	325	183	65	771	118
VS4-VS5	3258	1879	278	114	40	486	163
Entry ramp 2	674	259	38	1.9	1	13.57	674
Exit ramp 5	820	315	47	4.25	1	13.43	820
Entry ramp 3	581	223	33	1.6	1	13.7	581
Exit ramp 4	790	304	45	2.56	1	13.6	790
Entry ramp 6	1621	623	92	20.8	5	65.7	540
Exit ramp 2	960	369	54	4.5	1	13.43	960
Entry ramp 4	1615	621	92	30.87	6	78	538
Exit ramp 6	1612	620	92	30.87	6	78	538
Exit ramp 3	1465	563	83	15.44	4	52.6	733
Entry ramp 5	1035	398	59	5.58	2	26.86	1035
Entry ramp 7	1286	494	73	12.19	3	39.86	643

1 or 2 number of fans in the table 14 indicate the same location. However, based on longest section requirement and conservative approach, the number of fans are decided finally, and above numbers are not used. Here the minimum distance between the fans in all the ramps is considered as 118 m. Accordingly, the required number of fans are estimated for all the sections (see table 17).

1.7.7.2 Fully transverse System

Figure 10 shows a proposed arrangement of the duct for the fully transverse system. Additional arrangements to inject the fresh air near the pavement can be made by adding ducts on the side of the tunnels. However, this may limit the control in case these openings are to be used for extraction in some cases such as fire. Hence, currently the design is made using the arrangement shown in Figure 10. In the present tunnel the total cross-section height available for the duct is 2.75 m at the center. The corresponding total cross-section area available for the duct (A.F + A.V at the top in Figure 8) is 25 m². The total cross-section area is 105 m² and the required air flow rate is 325 m³/s. This results in a maximum velocity of about 26 m/s in the fresh air and exhaust ducts.

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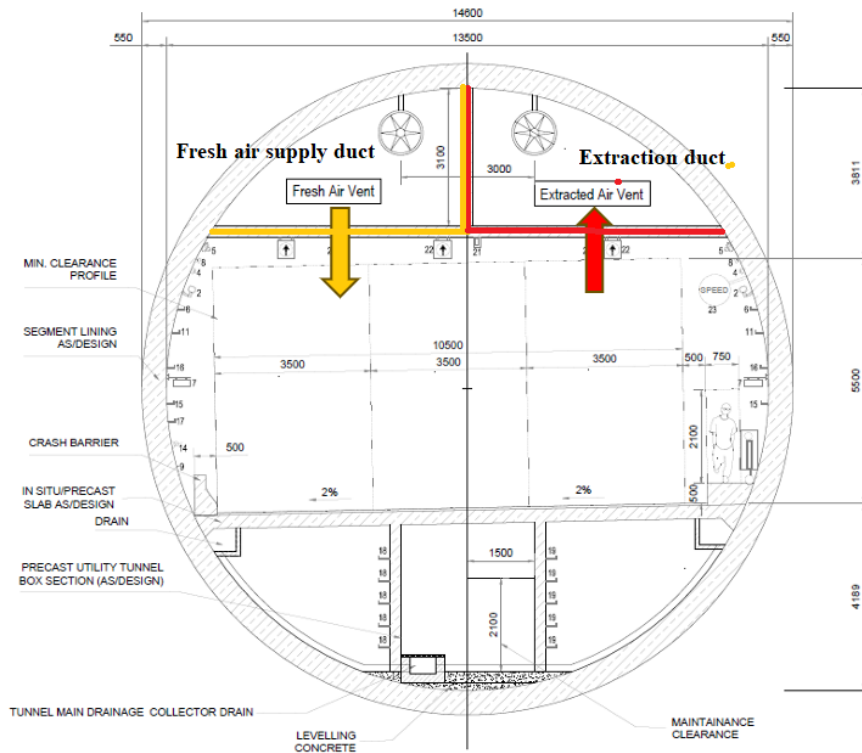


Figure 10: Duct arrangement for the fully transverse system in the cross-section

Figure 11 shows the longitudinal views of a sample arrangement. Longitudinally, two ventilation blocks are used to limit the maximum flow rates and velocities in the ducts. The dampers in fresh and the polluted air openings are directed towards the nearest walls. Longitudinally these are to be staggered. These blocks at one tunnel section are divided by the using butterfly flap.

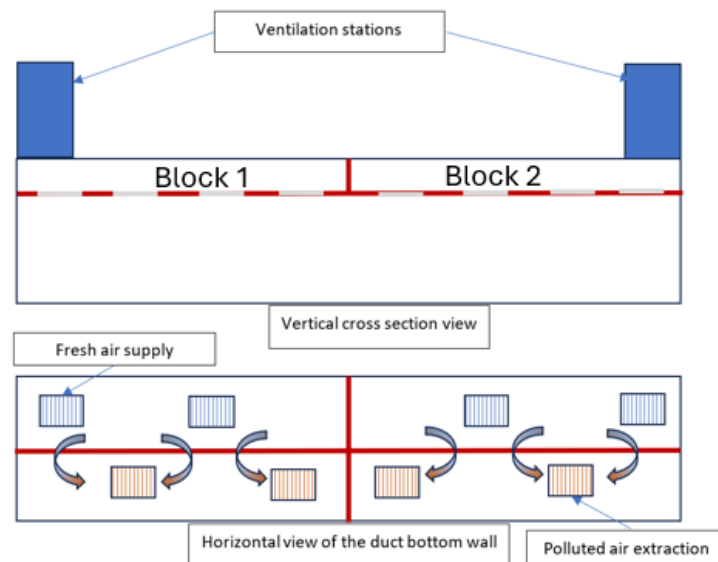


Figure 11: Schematic of the duct for fully transverse system (longitudinal views)

The friction losses and hence the pressure differences in the duct are calculated considering the variation of flow rates along the direction of flow. It is assumed that the flow rate and hence the velocity decreases linearly to provide a uniform air flow rate per unit length of the tunnel during normal operations. However, in case of a local congestion due to an accident or fire, this variation may change. So, the final power requirement will be enhanced to consider such scenarios.





Each block consists of the openings to the duct for fresh gas entry and for exhaust gas extractions. These openings fit with the dampers. These openings are of area 2.4 m² recommended for normal operations, which supplies the air to the tunnel sections with velocity around 4 m/s. Considering the fire and smoke removal requirements, the maximum area of the openings is recommended as 4 m. The area requirements are adjusted with dampers. The typical dimensions of the damper are recommended to be 1 m X 4 m.

Table 15 gives fan specifications used in the calculation of the fully transverse system for the longest section. Table 16 gives the design values arrived at using the highest air flow requirement for all four sections between the tunnel shafts, for a fully transverse system (Ref: PIARC, 1995).

Table 15 : Input values used for the fully transverse system design for the longest section

Parameter	Value	Remarks
Tunnel cross section area, m ²	80	After subtracting the duct area
Area available for air flow in the tunnel, m ²	70	Subtracting the vehicle cross section area
Ventilation duct area, m ²	12.5 × 2	Two ducts per block
Duct length, km	1.91	Two ventilation blocks
Fresh air rate, m ³ /s	163 × 2	For NOx; Two ventilation blocks
Pressure drop in duct, Pa	460	Per block
Fan flow rate, m ³ /h	90000	
Fan area (dia.), m ² (m)	0.79 (1)	
Pressure rise by fan, Pa	28	For the duct cross-section area
Total number of fans	17 × 4	Two fresh air ducts and two polluted air ducts
Distance between fans, m	115	Assuming two fans at one section
Type of fan	Traditional jet fan	
Power, kW	22	Per fan (minimum - estimated)

The pressure drop is calculated based on PIARC report 05-02-B.

Table 16 : Fully transverse system fan arrangements, estimated numbers, for each tube

Section Distance (m)		Total vehicles	Total NOx Emission (m ³ /s)	Air Flow Rate (m ³ /s)	Pressure Drop	No. of Fans	Total Power (kw)	Distance b/w Fans (m)
3570	Block1	536	152	152	381	26	572	136
	Block2	536	152	152	381	26	572	138
3625	Block1	544	154	154	398	28	616	131
	Block2	544	154	154	398	28	616	131
3820	Block1	573	163	163	460	34	748	115
	Block2	573	163	163	460	34	748	115
3258	Block1	489	139	139	296	20	440	169
	Block2	489	139	139	296	20	440	169

However, considering a conservative approach as mentioned before, and the ventilation during fire scenario, the total number of fans are estimated based on the longest section requirement.

1.7.7.3 Total number of fans in different sections for normal operations

The minimum distance between the fans with longitudinal and fully transverse calculations for different sections estimated as 118 m and 115 m respectively with minimum power requirement as 11.9 kW and 22 kW per fan respectively.

Based on these numbers and considering the conservative approach, the minimum distance between the fans is considered as 115 m and the power as 22 kW, for all the sections designed for both longitudinal and fully transverse system. Following number of fans are proposed conservatively for all the sections.





Table 17 : Proposed fan numbers in each section of the tunnel

Section	Section Distance (m)	Fresh air flow rate requirement (m ³ /s)	No. of Fans	Total Power (kw)	Ventilation system type	Layout package
VS1-VS2	3570	304	128	2728	Fully transverse	Package 1
VS2-VS3	3625	308	128	2728	Fully transverse	Package 1
VS3-VS4	3820	325	136	2904	Fully transverse	Package 2
VS4-VS5	3258	278	116	2464	Fully transverse	Package 2
Entry ramp 2	674	38	12	264	Longitudinal	Package 1
Exit ramp 5	820	47	14	308	Longitudinal	Package 1
Entry ramp 3	581	33	10	220	Longitudinal	Package 1
Exit ramp 4	790	45	14	308	Longitudinal	Package 2
Entry ramp 6	1621	92	28	616	Longitudinal	Package 2
Exit ramp 2	960	54	16	352	Longitudinal	Package 2
Entry ramp 4	1615	92	28	616	Longitudinal	Package 1
Exit ramp 6	1612	92	28	616	Longitudinal	Package 1
Exit ramp 3	1465	83	26	572	Longitudinal	Package 2
Entry ramp 5	1035	59	18	396	Longitudinal	Package 2
Entry ramp 7	1286	73	22	484	Longitudinal	Package 2

The 2 fans are placed at the beginning of the duct which increases the total count of each section between ventilation station by 4 fans. The half of the number of fans in sections VS1 to VS5 for each tunnel, are considered for fresh air injection and half of them for the extraction of the diluted air. 26 additional fans are provided to the ventilation inside cross-passages.

It is important to mention that, these design parameters are on overestimated side and are capable of handling any additional pollutant emissions.

1.7.7.4 Air flow exchange between the longitudinal and fully transverse system

As two different ventilation systems, longitudinal and fully transverse are considered for the entire tunnel system, the diluted air flow coming from the entry ramps will be directed to the corresponding main tunnel passages for extraction. Therefore, the extraction rate will be more for the main tunnel sections where the entry ramps are connected. The diluted air flow from the exit ramps will be directed to the exit locations of the ramps. The air flow rates to the exit ramps are also provided by the main tunnel sections wherever required. The details of entry ramps connected to different ventilation sections between ventilation station are given in following table 18.

Table 18 : Longitudinal and fully transverse ventilation system connections

Sections	Tube-1: Connected entry ramps (Esteem mall to CSB)	Tube 2: Connected entry ramps (CSB to Esteem mall)
VS1-VS2	-	Entry Ramp 4
VS2-VS3	Entry Ramp 3	-
VS3-VS4	Entry Ramp 6	Entry Ramps 5 and 7
VS4-VS5	-	-





The corresponding fresh air flow rate and required extraction rates are given in following table 19.

Table 19 : Flow rate handling between longitudinal and fully transverse ventilation system

Sections	Tube 1		Tube 2	
	Fresh air flow rate, (m ³ /s)	Extractor flow rate, (m ³ /s)	Fresh air flow rate, (m ³ /s)	Extractor flow rate, (m ³ /s)
VS1-VS2	304	304	304	396
VS2-VS3	308	341	308	308
VS3-VS4	325	417	325	457
VS4-VS5	278	278	278	278

Based on the flow rate requirements and number of fans available, the fan flow rate needs to be adjusted. Now, as the ventilation system is designed for the normal operation, in the next sections, the ventilation system design related to fire scenario is presented.

1.8 Ventilation during fire inside the tunnel

This section gives the designing the ventilation system during fire inside the tunnel. This involves following steps:

1. Choice of maximum heat load and design fire curve.
2. Selection of ventilation system
3. Design and dimensioning of the system
4. Design of firefighting systems.

1.8.1 Heat Release Rate and Fire Curve

The heat release rate and the design fire curve depend on the probable sources of fire. According to IRC-SP91-2019 (Section 5.9.1) the range of maximum heat release rate is 1.5–300 MW with a duration of this fire is 10 min. to 6+ days. The traffic mainly consists of passenger cars. For this type of vehicles, the range of heat release rate is 5–10 MW (Item 2 in Annexure F, IRC-SP91-2019). Along with this the electric buses are also allowed to enter and considering the possible allowance to other types of vehicles (LCV, HCV etc) a heat release rate of 30 MW for a duration 10 (to 60) minutes is chosen for the design. For this heat release rate, the range of smoke release rate is 20–300 m³/s (Section 5.9.1, IRC-SP91-2019). Assuming a linear correlation between the heat and smoke release rates a smoke release rate of 50 m³/s at the maximum gas temperature of 1350°C is taken.

1.8.2 Selection of Appropriate Ventilation System

In addition to the requirement of supplying fresh air in the normal operating conditions the ventilation system should consider the following aspects to handle fires in tunnels:

1. Pressurisation of the escape routes (such as cross passages) such that the smoke does not enter these regions from the tunnel with fire (Typical value is 50 Pa and a velocity of about 2m/s) (Section III.4 of PIARC Report 05.05 1999).
2. Proper stratification of the smoke such that sufficient time is available for people to reach safety.
3. Change of ventilation air directions to remove the smoke in the direction of lower number of people and vehicles.
4. The equipment such as jet fans should be selected such that they work at least for at least 2 hours with hot air (250°C) and smoke.
5. Enough number of fans to maintain at higher power to account for loss of some fans due to fire. The 10 % additional cost is recommended to be reserved for the same.

In the present case the traffic will be taken to be unidirectional and a “stop” condition in case of the kind of fire mentioned in the section on heat release rate.





1.8.3 Design and Dimensioning of Ventilation System for Fire Scenario

The design of the ventilation system to handle fire and smoke involves the following steps:

1. Estimation of the smoke release rate due to the fire (Section III.4 of PIARC Report 05.05 1999).
2. Verify whether the air flow rate required for the normal operation is sufficient to remove the smoke at an acceptable rate. If not, the systems will be re-designed either by enhancing the capacity or by adding a possibility of reversing the flow (Section III.4 of PIARC Report 05.05 1999).
3. Calculate the power of additional (possibly bi-directional) ventilation systems to be placed in the cross-passages and similar escape routes.

The required tunnel air flow rate and velocity are decided based on the following objectives:

1. Velocity should be more than the critical velocity required to avoid the back layering (flow of smoke upstream of the fire). Equation 5.7.1 in PIARC (1999) and PIARC (2017).
2. Flow rate should be sufficient to dilute the smoke to acceptable limits within the distance of extraction.
3. Flow rate should be sufficient to cool the stratified smoke to levels such that the radiation intensity on escaping people below that is safe. This is verified using 3D CFD calculations and suggested a safe distance.

The airflow rate requirement for the longest section leads to a tunnel air velocity of about 3.5 m/s, which is more than the critical velocity to prevent the back-layering. However, in shorter sections, the airflow requirement for pollutant dilution is less. So, from the point of view of smoke control in case of fire the same type of fans designed for longest section with the same distances should be used throughout the tunnel system.

In case of a longitudinal system, the expected smoke and toxic release rate of 50 m³/s at 1350°C will lead to an equivalent CO mass fraction of 1.5 % when mixed with the fresh air, which is much higher than the limit. This can cause harm to the people if the smoke is not stratified at the top of the tunnel for about 2.5 km. Preliminary 3D CFD simulations for a section of shaft with the required fire scenario shows that the smoke and toxic gases de-stratified very quickly in the tunnel and their concentrations can be much higher than the fatal limits beyond a few minutes. Under these conditions keeping the smoke stratified for such long distances is not possible unless it is extracted using point extractions or ducts. Since, intermediate single point extractions are not possible in the current tunnel, it is justified to use ducts and hence the fully transverse system of ventilation during fire scenario.

The same transverse system designed for the pollutant dilution with a minimum added 15% air flow rate (IRC_SP-91 2019, section 5.9.1) and 30% increase in power should be used as the power requirement is proportional to the square of the flowrate (section 4.2.2, PIARC, report 05.05.B).

1.9 Design of Fire Fighting Systems

According to the latest guidelines for Road Tunnels published by the Indian Roads Congress (IRC), the firefighting system of the tunnels must be equipped with:

- Fire detection systems
- Hand – Operated Fire Extinguishers
- Fire Hydrants
- Water Reservoir
- Fire – Hose Coil with Supply
- Sprinklers

The firefighting equipment and their placement remains the same for both the ramps (entry/exit sections) and main tunnel sections. Both these types of sections are provided with jet fans, fire detection systems, fire extinguishers, fire hydrants and sprinklers placed at same distances. These also include the secondary substation niches.

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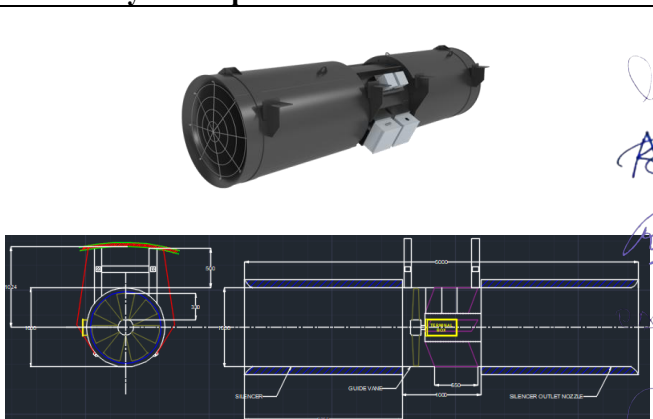


Following recommendations are given in IRC_SP-91 (2019), PIARC 05.05.B (1999) and NFPA 502:

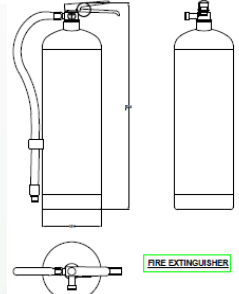
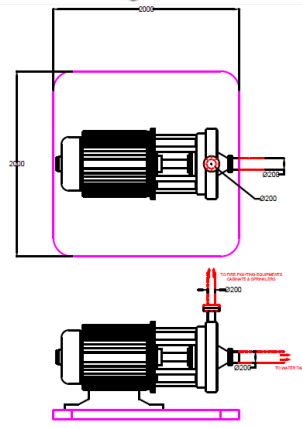
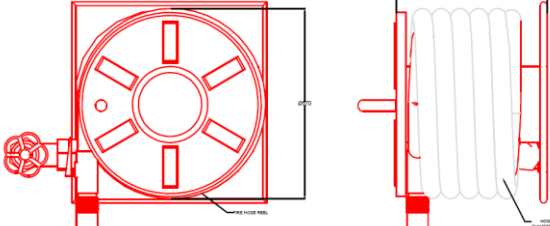
- Fire detection systems include detectors of heat (temperature and rate of rise), smoke, and flame. In addition, there are spot and linear heat detectors. LHD will be used in the tunnel and spot detectors shall be used inside the duct too. Automatic fire detection systems shall be capable of identifying the location of the fire within 15 m (50 ft). Automatic fire detection systems shall be able to detect a tunnel fire incident of 5 MW or less within 90 seconds or better in a testing environment of 3 m/sec (590 fpm) air velocity. Fire alarms are recommended to be placed at every 100 m which are inline with other firefighting equipment, while the fire alarm sensor at every 20 m as per section 7.4.6.6.4 of NFPA502. This meets the requirements of both the standards and permits some redundancies.
- The fire extinguishers should have a minimum content of 6 kg. They should be rated for liquid, grease and electrical equipment fires. The maximum distance between fire extinguishers recommended to be of 90 meters as per section 7.9 of NFPA502.
- It is recommended that all road tunnels of sufficient length (200 to 1000 m according to the case) be provided with a water supply standpipe installed through the length of the tunnel. This standpipe should have a minimum capacity of 1000 l/min at 0.5 MPa (PIARC, report 05.05.B, 1999, section 6.3.3.3). The standpipes are wet type. Hydrants should be placed at a spacing of 90 to 200 m. The between hose connections is recommended to 85-90 meters (section 10.4, NFPA 502). The fire main and hydrants shall be placed in such way that the walkway width remains clear of this. The connections between the main tube sections and entry/exit ramps are possible through the utility spacings. It can also be carried out using hose bridge on connectors. The utility spacing is also provided to connect the standpipes between cross-passage and main tunnel section. The appropriate sealing will be used to avoid the depressurization, and this shall be carried out by the concessionaire during the detailed design place. The installation cost recommended to be considered for the firefighting system.
- The total capacity of the water tank shall be sufficient to provide water supply for 60 minutes of operation. The tanks shall be placed closed to the pump room and are recommended to be built at ventilation stations.
- Sprinkler systems are a type of fixed fire suppression system (FFS) that can be used in tunnels to help prevent fire spread and cool the tunnel structure. Sprinklers systems in full scale road tunnel experiments are found to be efficient in fire-fighting mechanism. ("Performance of water-based fixed firefighting systems in road tunnels: A review" by Tao Deng et.al.). As the tunnel is located in urban environment and considering the lengths of tunnel sections which are more than 3 km and the traffic flow conditions, the present tunnel falls in category AA (Figure 9.2) defined in IRC_SP-91 2019, section 9.5.2. For this, sprinkler in firefighting equipment are mandatory (Table 9.1). The sprinkler arrangement is recommended to be used at every 4 m

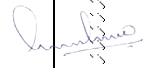
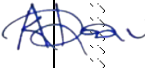
Firefighting systems also include the jet fans and pumping system. The specifications of the same along with other firefighting equipment are given in next section.

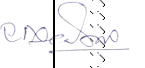
1.9.1 Firefighting equipment and specifications

Equipment	Technical Specification	Physical representation with sketches
Jet fan	• Flow rate: 25 m³/s • Bi-directional with 2D silencers at both ends. • Static pressure: 500 Pa • Thrust: 750N. • Operating voltage: 415V (3-phase 50Hz) • Fire rating: 250°C, 2 hr temperature rating.	



Equipment	Technical Specification	Physical representation with sketches
Fire extinguishers	6Kg ABC Dry Powder (Stored Pressure) type - Pressurized with dry nitrogen gas at 15 bar.	 
Pumping unit	Electric Pump: - Axial suction, radial impulsion - Stainless steel shaft 4660 lt/min, head of 350 m rated 2900 rpm 2 poles three-phase asynchronous motor (415 V, 50 Hz) - Protection: IP55 - Power: 150 kW - Pressure range 3.5 kg/cm² at the farthest sprinkler/hydrant point Diesel Pump: - Horizontal centrifugal end suction type 4660 lt/min, head of 350 m rated 2900 rpm - CI casing, CI impeller. Auxiliary Jockey Pump: - Vertical Multi in line type fire pump 2900 RPM capable of delivering 460 lts/min against a head of 350 m. 415V, 3phase, 50Hz - Bronze impeller - Power: 1.5 kW - Protection: IP55 - Shaft isolation with mechanical closure	 
Fire Hydrant and hose connection	Fire hydrant - Type C (according to EN 14384 standard) with anti-icing system, helical spring closure - Nominal pressure: 16 bar Hose pipes 100 mm diameter 23 kgf/cm² pressure	 








Equipment	Technical Specification	Physical representation with sketches
LHD	- Fixed temperature set point or Rate of rise temp setting with Programmable alarm - Operating temp (-20 °C to 70 °C) with alarms for open circuit and short circuit - Standard fixtures as required and duly approved by LPCB / EN54	
Fire alarms	- EN54 approved fire alarm control panel - Panel: expandable, networkable, having option to interface to BMS with optional interface of LON Works, BAC net & MOD Bus, with a battery backup of 24hrs in normal condition and 30min in alarm condition. - Multi sensor with optical smoke element and thermal element. - Detector: facility to mount in different comprehensive places as required and duly approved by LPCB / EN54.	
Sprinklers	Above ground pipes - MS pipes "C" class - Pressure rating: 11Kg/cm² for 8 hours - Diameters: 200 mm, 100 mm, 32 mm, 25 mm Sprinkler bulbs: 15mm diameter nominal bore quartzoid type - Temperature rating of 68 / 93 °C of K-80 factor - Pendant type of 93 °C	

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It is important to note that the VFD panels are used to start, stop and control the speed of the motor of the fan, which is important to manage both the normal and emergency operations. Any additional flow requirement can be managed. However, the soft starters are used to start and stop the motors and only efficient with fixed defined speeds. VFD panels are also energy efficient and increases the equipment lifespan. Hence VFD panels are recommended.

1.10 Emergency and evacuation

The strategic planning of safety and evacuation during fire, accident and during vehicle breakdown inside tunnel is important in tunnel designing process. As a first step, in the event of an incident in the tunnel, the alarm can be raised by video surveillance or by more specific means such as (IRC: SP-91-2019):

- Emergency telephones (call stations)
- Notification of door opening (cross-passages) or removal of a fire extinguisher from its hook,
- Alarm push buttons (manual call points),
- Automatic incident detection (by analysing CCTV images),
- Fire detection systems.

In any case, it is important to evacuate early and fast. Therefore, in addition to providing an emergency route to a safe place, measures are required to make sure people react quickly and evacuate early through the emergency exits.

During the emergency scenario, the ventilation system aims to create and maintain a tenable environment for the evacuation of tunnel users. Specifically, this environment consists of acceptable visibility and air quality levels. In general during emergency operation, the most important thing is to evacuate quickly on foot, following the designated exit signs, driving out of the tunnel if possible, and never stopping your vehicle unless absolutely necessary; if it has to be stopped, one must proceed on foot to the nearest exit, always prioritizing the safety over belongings (PIARC Ref.: 2012R25EN).

For the discussion of safety and evacuation strategies in the present twin tube tunnel, two locations are considered, one inside the entry and exit ramps and other one inside the main tunnel passage.

1.10.1 Fire or accident near the entry and exit ramps

If there is a fire inside entry or exit ramps near the main tunnel section (up to 100 m from the main tunnel section) the hot smoke will be blown towards the open side by means of the jet fans. The nominal value for the velocity of the tunnel airflow downwind the fire lies between 1.0 m/s and 1.5 m/s.

The entry to the corresponding ramp and the main tunnel tube will be stopped. The vehicles at the open end will be diverted to alternate routes by providing appropriate signage boards. The vehicles upstream to the fire inside ramps must be evacuated through the entry or exit locations. The passengers upstream and close to the fire location are required to walk towards the open end, while downstream vehicles will be allowed to travel further. In the corresponding, where this ramp is connected, main tube the vehicular movement is stopped upstream to the smoke or will be diverted through the cross-passages to other tube. and the vehicles will be allowed to go out to main tube in the downstream direction. The schematic of fire inside the ramps is shown in the following figure 12.



Figure 12: Schematic of fire inside entry or exit ramps

In case of fire in the entry and exit ramp near the open cut, the fire and hot smoke will be blown away through the open area. The vehicles inside the ramps in the downstream directions will be directed towards the main tunnel sections (vehicular movement in the main tunnel is controlled accordingly) and the entry to the ramp will be closed.





During the vehicle accidents, the vehicles inside the ramp and close to main tunnel section will be diverted towards the main tunnel section. Entry to the ramps will be closed. The spacing shall be provided to the ambulance to have access to the accident site.

Detailed SOP for the same shall be drawn by the concessionaire.

1.10.2 Fire in the sections between the ventilation stations

If there is a fire within the ventilation stations 1 to 5, detected hot smoke will be extracted through the dampers. In this scenario, the exhaust air fans will be operated at their maximal power in order to get the maximum available extraction output. The jet fans are operated so that it is possible to avoid an expansion of the hot smoke gases in the tunnel on the one hand and on the other hand to ensure an equal afflux of the fresh air upwind of the fire location to the extraction point. It is also suggested to operate both the jet fans, fresh air and exhaust air, in extraction mode to increase the smoke extraction rate and the fresh air is expected to enter in the tunnel sections through the entry and exhaust ramps in this case.

The cross-passages will be used as emergency exit which connect main tunnel tubes. These are located at every 500 m connecting the road tunnel with the other side tunnel. In case of a fire the people can leave the hazard zone via this evacuation route. In order to keep this emergency and rescue path free from smoke, a shear wall with an emergency door is proposed, if possible, for each cross passage. These emergency doors or the main doors have to be equipped with an assisted electrical or mechanical opening system to ensure moderate opening forces of the emergency doors. It is also recommended to have the centralized control to the emergency openings. Doors also to be Fire rated for a minimum of 90 minutes. In addition to that these walls are equipped with a pressure difference measurement to control the pressure difference between the road tunnel and the cross-passages.

The minimal air flow velocity through an open door of the cross-passage has to be 2.5 m/s in direction to the road tunnel where the fire is located. This means, that the pressure in the emergency and other side of the tunnel has to be higher than the pressure in the incident tunnel. In case of a fire and unfavourable meteorological conditions the pressure in the incident tunnel can reach up to 360 Pa (plus ambient pressure).

During this kind of emergency, all the entries to the main tunnels will be closed. The passengers within the range of 100 m to the fire location, need to get out of the vehicles and walk towards the nearest cross-passages in the opposite direction to smoke.

In tunnels with two tubes operating with unidirectional traffic and with transverse ventilation, the ventilation typically supports smoke propagation in the driving direction (the initial direction of smoke propagation due to traffic-induced airflow). The smoke gradually affects the empty part of the tube in front of the incident. People that are stuck in traffic behind the incident can be evacuated to the other tube and are normally not affected by the smoke. The second tube will normally be closed to traffic and can be considered a safe zone to evacuate to.

In case of accidents, the entry to the corresponding tube is closed and the traffic upstream to the accidental location is either stopped or diverted to other tunnel tube through the cross-passage. The injured people are rescued or the passage to the ambulances are provided from the nearest possible entries. One lane is made available for the same. The traffic downstream to accidental location is allowed to go out of the tunnel. The typical schematic of the fire and evacuation inside the main tunnel section is shown in the figure 13 below.

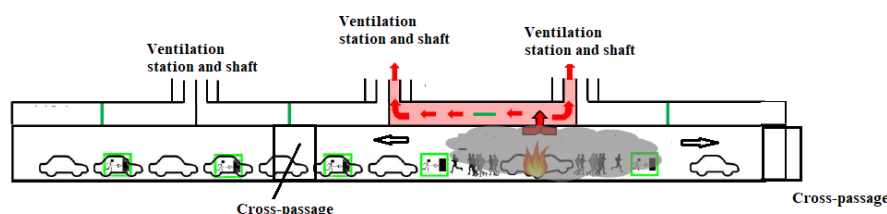


Figure 13: Schematic of fire inside the main tunnel

1.11 Positioning of entry and exhaust ducts inside tunnel ventilation station

The positioning of the entry and exhaust ducts at the ventilation station is important to avoid the mixing of polluted air extracted from the exhaust duct to the fresh air entry duct. In the present design, the positioning of the ducts are considered at the two ends of the ventilation stations as shown in the following figure 14.



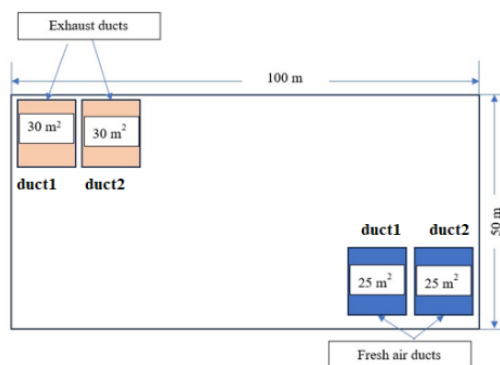


Figure 14: Positioning of the intake and exhaust ducts at the ventilation station

The duct 1 and duct 2 indicate the ducts attached to the two tubes. The sizing of the entry and exhaust ducts decided based on the sizing of the ducts of the tunnel. Current positioning of the intake and extractor ducts make sure that the concentration of CO and NO_x coming out of the extractor ducts reduces by 90% before reaching to the fresh air ducts. The typical dilution rate of CO and NO_x from extractor ducts to fresh air ducts at the Lalbagh ventilation station is shown in figure below.

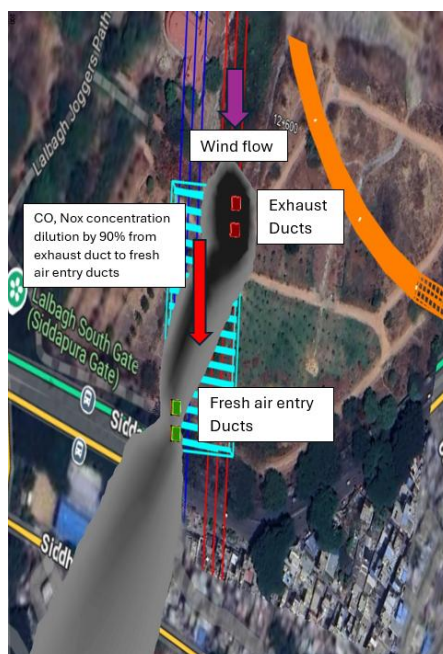


Figure 15: Dilution pattern of the CO and NO_x from exhaust ducts to fresh air ducts (Lalbagh station): black color indicate the extracted air.

1.12 Recommendation for the whole tunnel ventilation system

Considering both the normal and emergency operations discussed in previous sections, it is recommended to use the fully transverse ventilation system in the main tunnel sections between the ventilation stations. However, for the entry and exit sections, (entry ramp2, exit ramp 5, entry ramp 3, exit ramp 4, entry ramp 6, exit ramp 2, entry ramp 4, exit ramp 6, exit ramp 3, entry ramp 5, and entry ramp 7), the longitudinal system is sufficient to use. This is tabulated in following table 20.

Table 20 : Proposed ventilation systems for entire vehicular passage of underground tunnel

Sections	Ventilation system	Flow exchange points	Package
Entry ramp2, Exit ramp 5, Entry ramp 3, Entry ramp 4, Exit ramp 6	Longitudinal	Exit locations or the main tunnel sections	1
Exit ramp 4, Entry ramp 6, Exit ramp 2, Exit ramp 3, Entry ramp 5, and Entry ramp 7	Longitudinal	Exit locations or the main tunnel sections	2



Sections	Ventilation system	Flow exchange points	Package
Sections VS1-VS2, VS2-VS3, between ventilation stations	Fully transverse	Ventilation stations (shafts)	1
Sections VS3-VS4, VS4-VS5, between ventilation stations	Fully transverse	Ventilation stations (shafts)	2

Due to differences in lengths of tunnels, the individual ventilation sections require different air flow rates and hence different number of fans and power. However, to ensure the minimum flowrate and velocity to deal with a fire scenario it is recommended to use the air flowrate and power requirement estimated for the section with highest effective length for the whole system of the tunnel. At this stage, the overall implementation effort and cost of the system may be estimated using this basis. In this case, these values are calculated for a transverse system. These values are for the ventilation system to dilute the pollutants. The maximum flowrate for the fans has to be increased by 15 % and the power by 30 % keeping the distance between them same.

Table 21 : Total fan requirements for whole tunnel ventilation system

Property	Value
Number of fans	750 (Transverse-508, longitudinal 242)
Flow rate, m ³ /h	90000
Fan area (dia.), m ² (m)	0.79 (1)
Pressure, Pa	32 (for the duct cross section area)
Power per fan, kW	30
Distance between fans, m	115 (with two fans at one place)

The longitudinal fans involve the fans for cross-passages also. Total minimum estimated power requirement for operating fans is 22.5 MW considering the fire scenario. Considering the power load for other equipment's, it is suggested to design the tunnel system for 30 MW power. The cross-sectional view of the one tunnel tube with ventilation system and fire-fighting equipment's is shown in following figure 16.

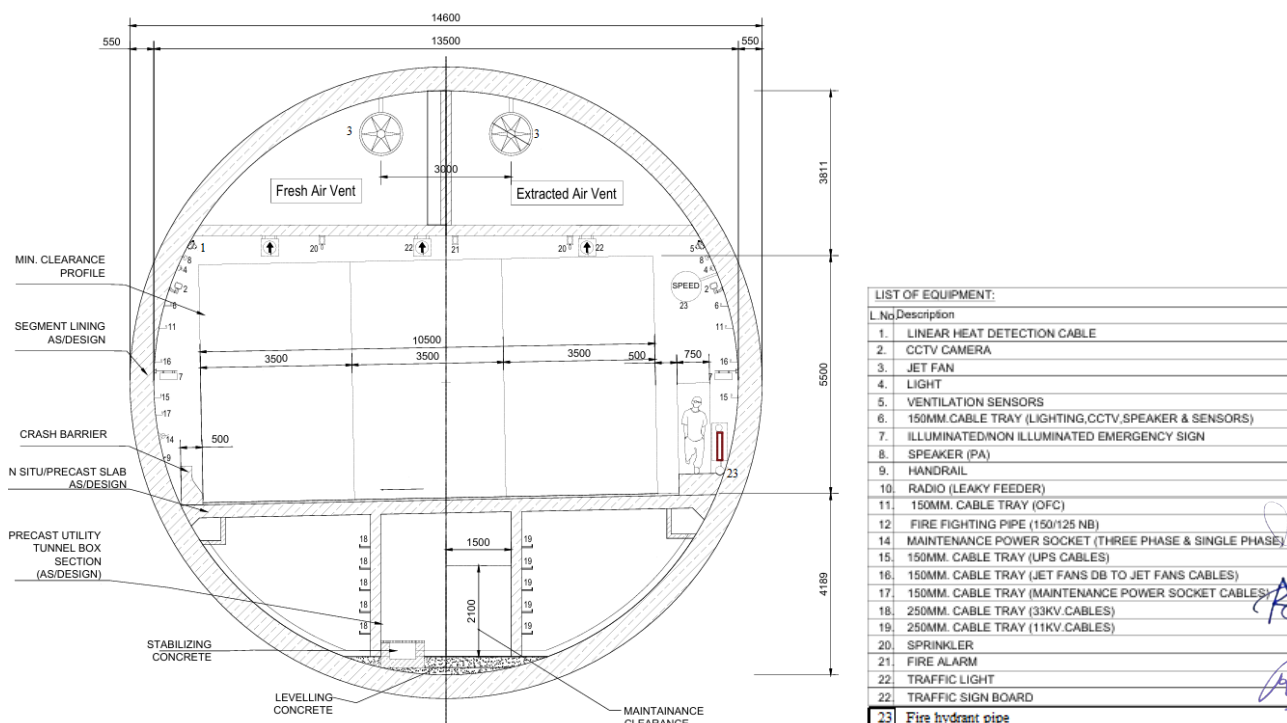


Figure 16: Typical cross section with ventilation system and fire-fighting equipment's

It is important to note that the cost-estimation of the ventilation system design also includes the shaft building ventilation system, included with primary substations. However, the details for the same shall be provided by the concessionaire depending on the area, location and planning for the utilization of spaces in





these buildings at shaft locations

1.13 Computational Analysis to Verify the Designed Ventilation System

The ventilation system is designed in terms of dimensioning and positioning of the system equipment's, same design is verified for both the normal and emergency operations (fire) using the computational analysis. This includes the simulation and estimation of following parameters for a particular traffic condition:

5. Vehicle emissions
6. Tunnel air flow
7. Fan flow
8. Ventilated air flow distribution and quality assessment
9. Fire simulation and smoke extraction

These parameters are analysed for a particular section of interest (here the longest section) to verify the designed ventilation system for its dimensioning and positioning of equipment. Computational analysis is performed with very well validated commercial software. The detailed report is given in the Section 2.

1.14 References

1. BBMP, Request for Proposal for the “Consultancy services for preparation of DPR for the work of Construction of Underground Vehicular Tunnel from Hebbal Esteem mall junction to Silk Board KSRP junction”, 2024.
2. IRC, Guidelines for Road Tunnels, IRC: SP-91-2019, 2019.
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6. PIARC, Fire and Smoke Control in Road Tunnels, Report 05.05.B, 1999.
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8. PIARC, Vehicle Emissions, Air Demand, Environment, Longitudinal Ventilation, Report 05-02-B, 1995.
9. PIARC, Best practice for road tunnel emergency exercises, Report 2012R25EN
10. NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways
11. Tao Deng, Stuart Norris, Mingnian Wang, Li Yu, Zhiguo Yan, Rajnish N. Sharma, “Performance of water-based fixed firefighting systems in road tunnels: A review”, 2025

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2 VENTILATION SYSTEM DESIGN VERIFICATION

2.1 Introduction and Context

Bangalore, the bustling capital of Karnataka, is known for its rapid urbanization and exponential growth in vehicular traffic. As the city expands, the need for advanced infrastructure to accommodate increasing traffic demands and enhance road safety has become paramount. Among the critical solutions advised by experts, is the development of road tunnels to streamline traffic flow and reduce congestion in key areas. In this view, Bruhat Bengaluru Mahanagara Palike intends to Construct an Underground Vehicular Tunnel for the North – South Corridor starting from Hebbal Esteem Mall junction to Silk Board KSRP Junction.

Given the complexity and safety considerations of such a project, a robust and well-designed tunnel ventilation system is essential to maintain adequate air quality within the tunnel during normal and heavy traffic situations, while also facilitating self-evacuation and rescue efforts during emergencies such as during fire scenario. Moreover, the ventilation system's ability to handle emergency situations, primarily to manage smoke and hot gases in the event of fires, needs to be thoroughly assessed and designed to satisfy these specific requirements.

For the proposed underground vehicular tunnel from Hebbal Esteem mall junction to Silk Board KSRP junction, the fully transverse ventilation system is designed considering both natural and fire scenario. To verify the same design, the computational fluid dynamics (CFD) approach is proposed.

2.2 Layout of the proposed tunnel

The proposed tunnel consisting of unidirectional twin-tube system. Figure 17 shows the tunnel cross-section of the tubes. Inside diameter is 13.5 m. Vehicle clearance is 5.5 m. Free space available is 3.22 m, out of which 0.5 m is required for signs. The pavement is 2.6 m below the centre. Each lane is 3.5 m. The cross-section area is 105 m².

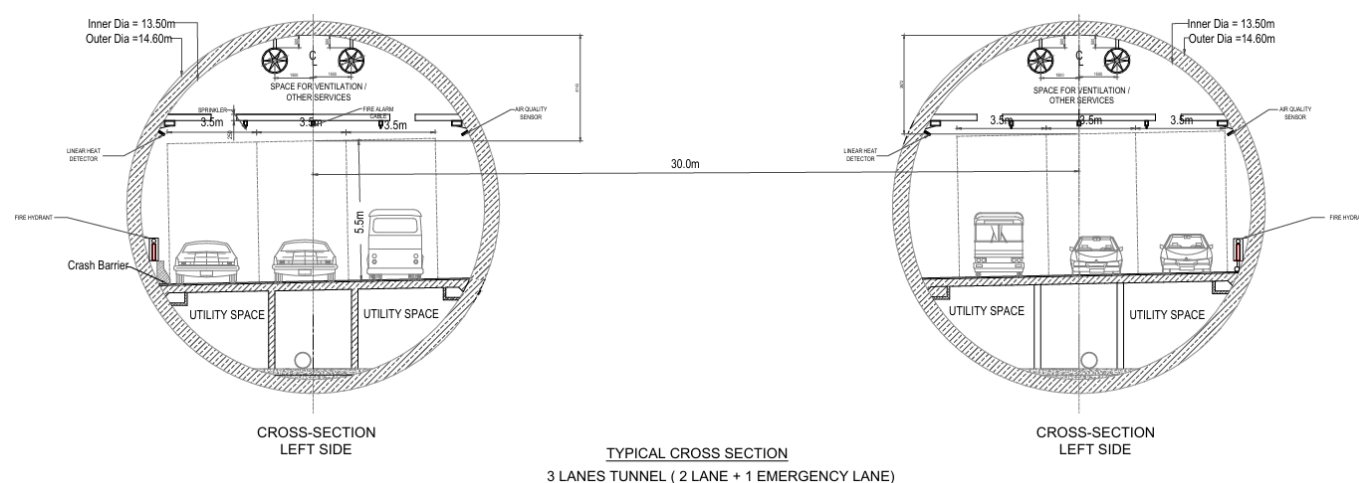


Figure 17: Cross-sectional layout

The tunnel is 16.7 km long, consisting of entry and exit points on both tubes of the tunnel. There are several entry tunnels and four exit tunnels. From ventilation system point of view, 5 ventilation stations positioned at various locations throughout its length. The sections between the ventilation systems are not equidistant. Figure 18 shows the schematic of the tunnel sections with the ventilation systems.



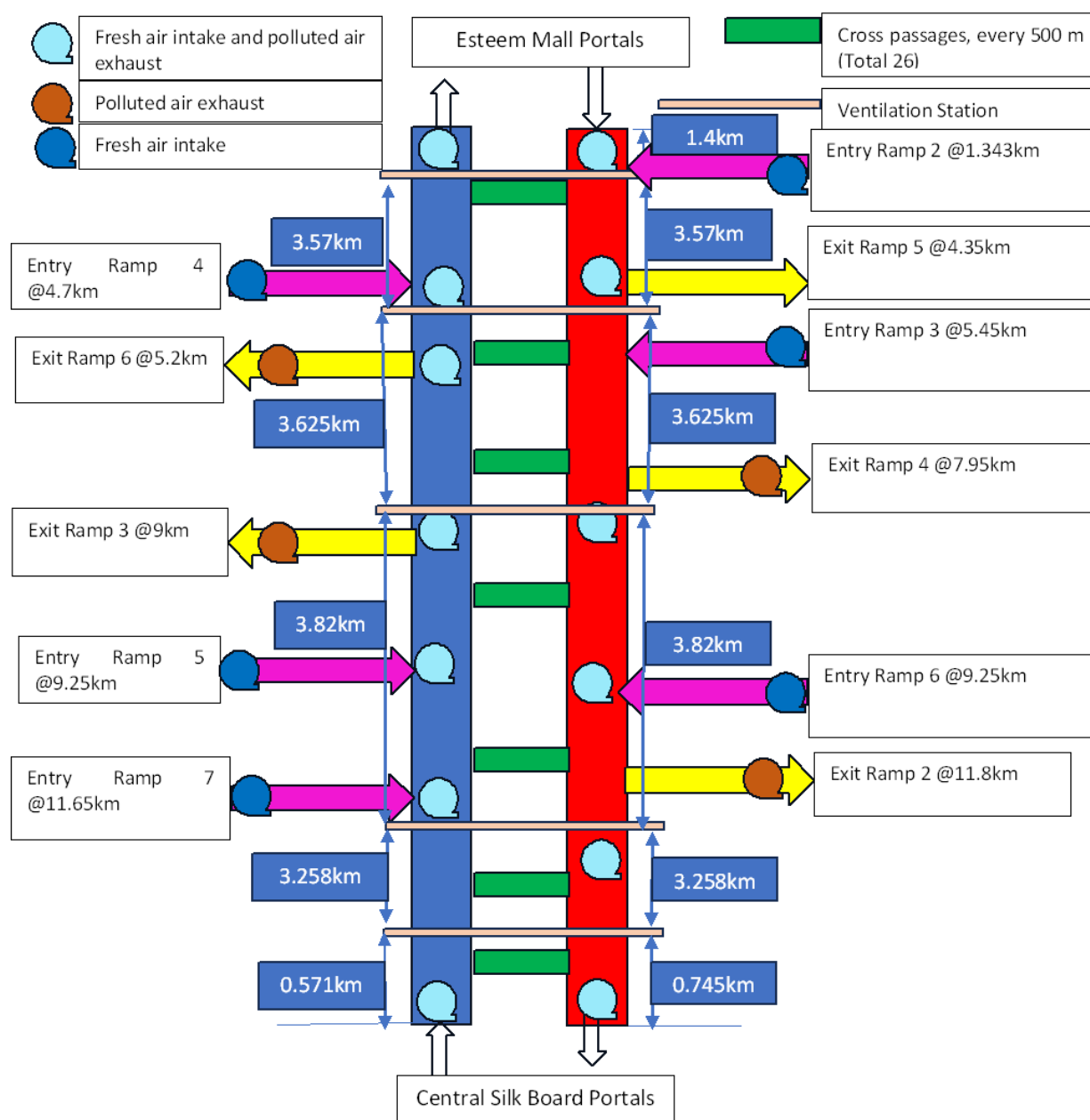


Figure 18: Ventilation Sections

The section lengths throughout the one of the tunnel tubes are given in table below:

Table 22 : Section lengths (VS0 and VS6 are the main entry and exits)

Ventilation Sections	Distance from Esteem Mall to the farthest station, m	Length of section, m
VS0 - VS1	1400	-
VS1-VS2	5100	3570
VS2-VS3	8725	3625
VS3-VS4	12625	3820
VS4-VS5	15970	3258
VS5-VS6	16745 (Tube 1)	-
	16571 (Tube 2)	-

Due to differences in lengths of tunnel sections, the individual ventilation sections require different air flow rates and hence different number of fans and power. The longest Tunnel section in this case is around 3.82 km.



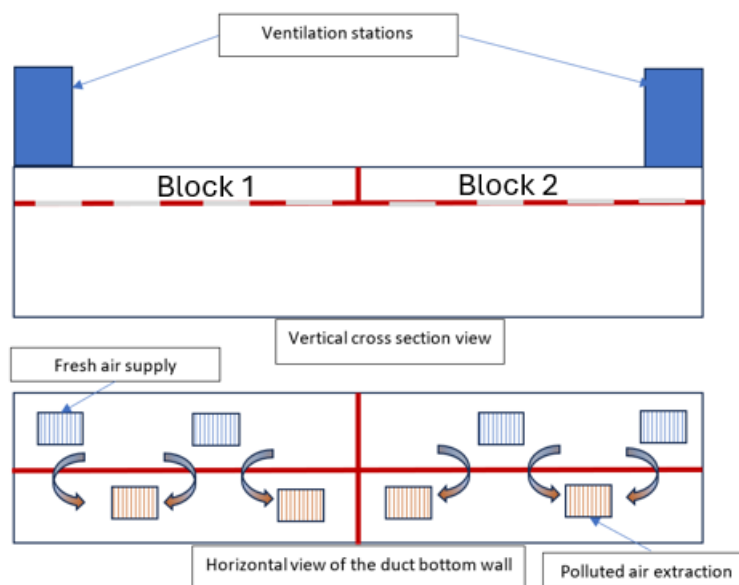


Figure 20: Schematic of the fully transverse system

The fully transverse system designed parameters for the longest section are tabulated in the table below:

Table 23 : Transverse ventilation system parameters

Parameter	Value	Remarks
Tunnel cross section area, m ²	80	After subtracting the duct area
Area available for air flow in the tunnel, m ²	70	Subtracting the vehicle cross section area
Ventilation duct area, m ²	12.5 × 2	Two ducts per block
Duct length, km	1.91	Two ventilation blocks
Fresh air rate, m ³ /s	163 × 2	For NO _x ; Two ventilation blocks
Pressure drop in duct, Pa	460	Per block
Fan flow rate, m ³ /h	90000	
Fan area (dia.), m ² (m)	0.79 (1)	
Pressure rise by fan, Pa	28	For the duct cross-section area
Total number of fans	17 × 4	Two fresh air ducts and two polluted air ducts
Distance between fans, m	115	Assuming two fans at one section
Type of fan	Traditional jet fan	
Power, kW	22	Per fan (minimum - estimated)

2.4 Objective

The objective of this work is to verify the proposed fully transverse ventilation system design for both normal operations and fire scenario using the CFD analysis. The normal ventilation system verification is related to the assessment of the airflow distribution and air quality inside the tunnel. The fire simulation involves the evaluation and the verification of the designed ventilation system's effectiveness in smoke control during fire incidents.

2.5 Methodology

The steady state flow simulations are performed first, then the normal operation and fire scenarios are simulated using the steady state flow results.

This study will be done for two phases:

1. **Phase 1:** 3D CFD simulation of normal ventilation operation in case of traffic congestion
2. **Phase 2:** Fire simulation





2.6 PHASE 1: 3D CFD simulation of normal ventilation operation in case of traffic congestion

2.6.1 Present section includes the description of geometry modelling, mesh structure, numerical inputs and results obtained

2.6.1.1 Geometry Modelling

For the CFD analysis purpose only one tube of the tunnel is considered as the cross-passages are usually closed. Only half of the longest section length is considered. shows the modelled geometry of the same. The blue cylinders represent the fans for fresh air insertion and the red cylinders represent the fans for exhaust air extraction. The longitudinal distance between fans are maintained to 115 m as per the design and total 17 fans are considered for this section. The cuboidal objects represent the vehicle at the tube of the tunnel.

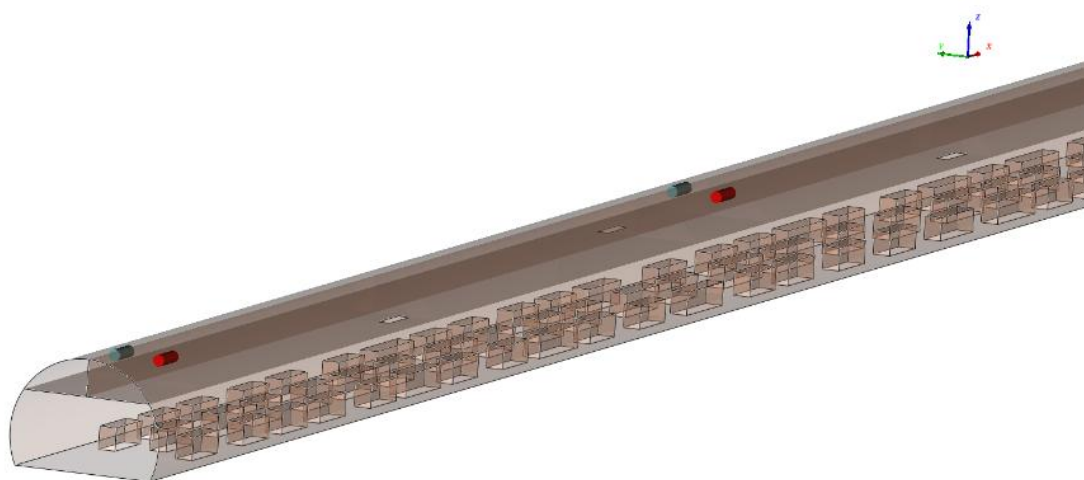


Figure 21: Tunnel Section Geometry

The duct is divided into two parts by a partition wall as shown in figure 22. The blue part represents the fresh air duct portion and the red part as the exhaust duct. Figure 23 shows the top view of the staggered arrangement of the openings of both the ducts. These openings allow the fresh air flow to the tube and then the polluted air flow to the exhaust duct.



Figure 22: Tunnel cross-sectional view

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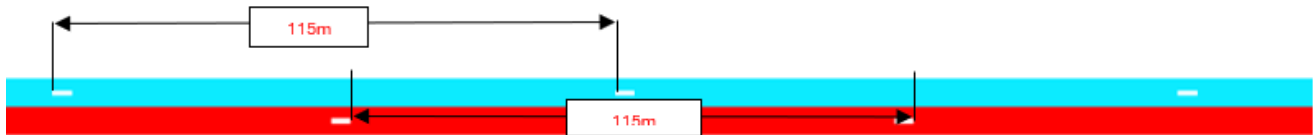


Figure 23: Openings of the ducts

The blue colour represents the fresh air duct and the red colour represents the extractor duct. Figure 24 shows the arrangement of the fans.

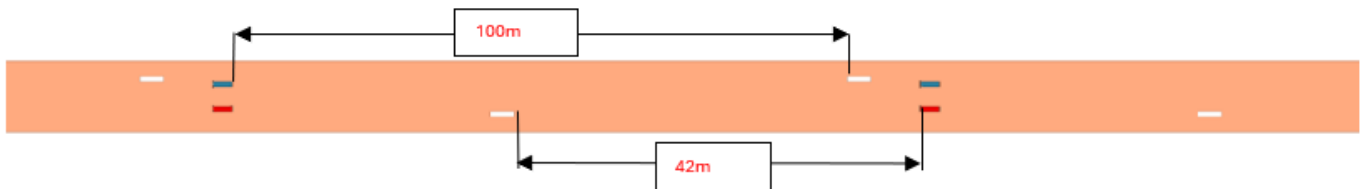


Figure 24: Openings and Fans inside the duct

2.6.1.2 Mesh Generation

The mesh is generated using Fluidyn-MP. Figure 25 shows the zoomed-out view of the mesh of the tunnel, where the fresh air duct, exhaust duct, tube and vehicles inside the tube of the tunnel are displayed. The placement of openings is shown in figure 26.

The mesh statistics is detailed in table 24

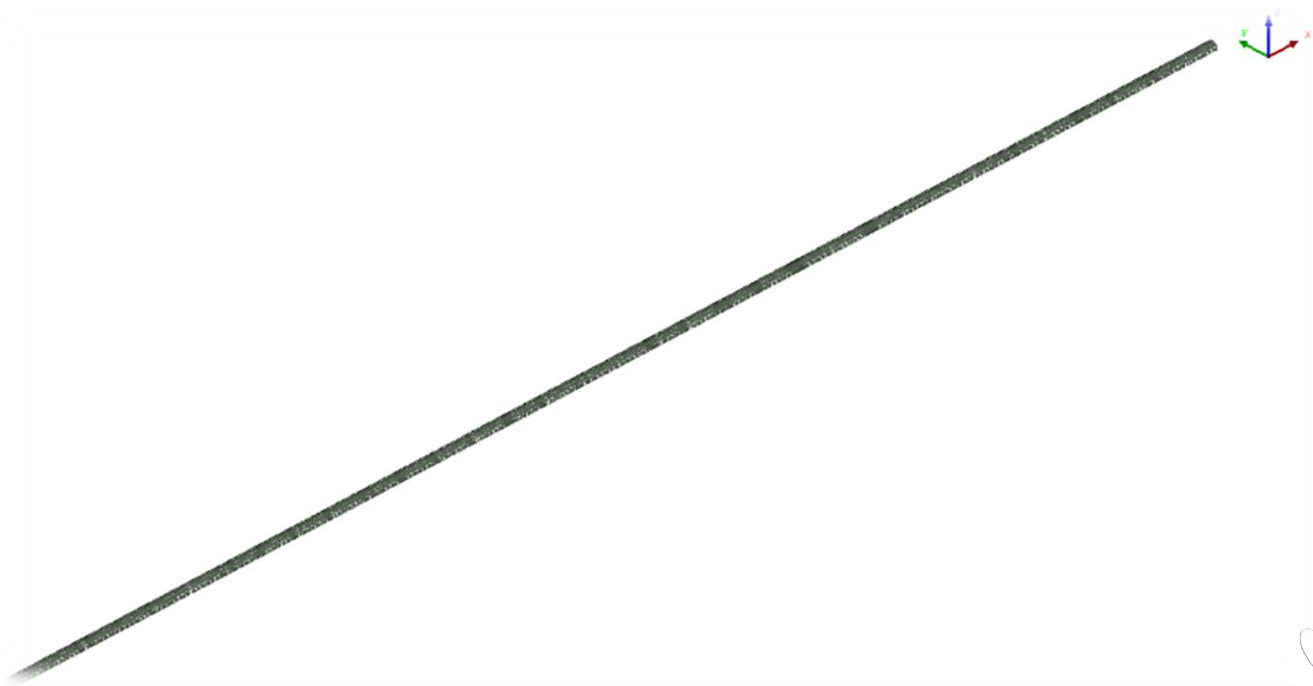


Figure 25: Tunnel Section Mesh

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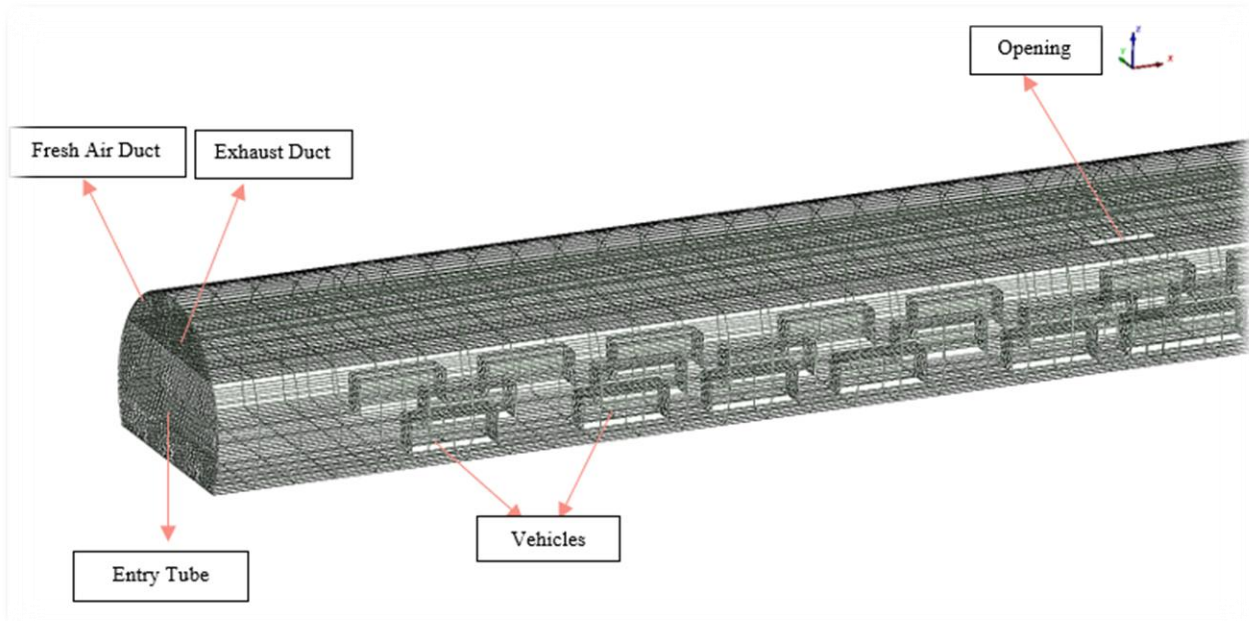


Figure 26: Tunnel mesh and nomenclature

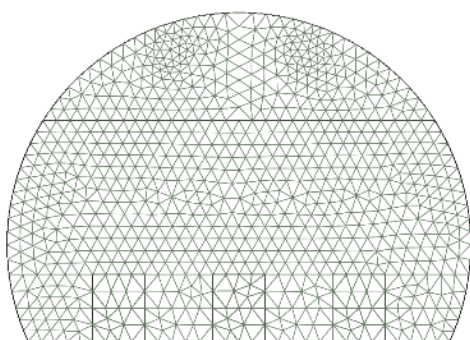


Figure 27: Cross-sectional view of mesh

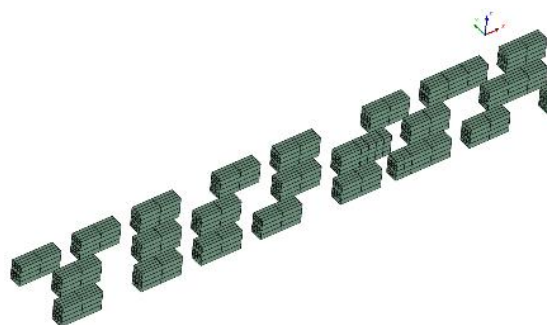


Figure 28: Vehicles mesh

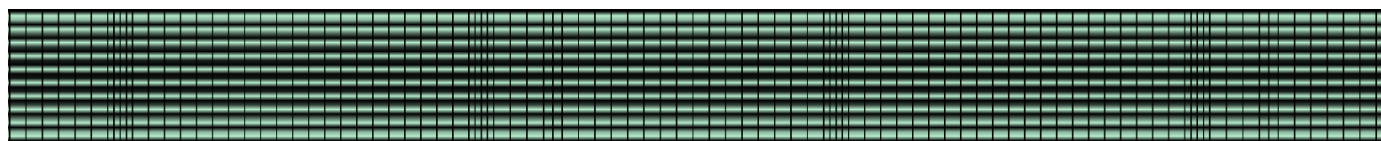


Figure 29: Top view of Openings in the ducts

Table 24 : Mesh Statistics

No. of elements	No. of nodes	Type of elements
1324638	753580	Wedge

2.6.1.3 Numerical parameters

The air is considered as the fluid material, and its properties are given in the following table.

Table 25 : Fluid material properties

Fluid Material	Molecular Weight	Viscosity, Pa-s	Density, kg/m3
Air	28.97	1.71e-05	1.2

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The pollutant emissions such as CO₂, NO₂ and PM are modelled in terms of passive scalars.

The steady state fluid flow analysis is carried out considering the incompressible fluid flow. The turbulence is modelled using standard k-ε model. Pressure velocity coupling is realized through the SIMPLEC algorithm, and first order upwind discretization scheme is as convection scheme.

2.6.1.4 Boundary conditions

In the tunnel section considered, the vehicle direction is from left to right end. The right-side surface of the tunnel is assigned with symmetry boundary condition, while the right-side surfaces of the ducts are assigned with wall boundary conditions.

The designed fresh air flow rate required to maintain the admissible air quality during the normal operation is 163 m³/s. This is realized by assigning the velocity boundary condition at the left side surface of the fresh air duct. In order to maintain the same momentum corresponding to this flow rate, the 17 fans are assigned with velocity equivalent to the distributed flow rate. The polluted air is extracted through the extractor ducts, which is assigned with pressure static boundary condition. The fresh air flow of 1 m/s is considered at the entry of the tunnel (left side surface). All the other surfaces are considered as no-slip walls.

The CO, NO₂ and PM emissions are released from the bottom surface of the tunnel.

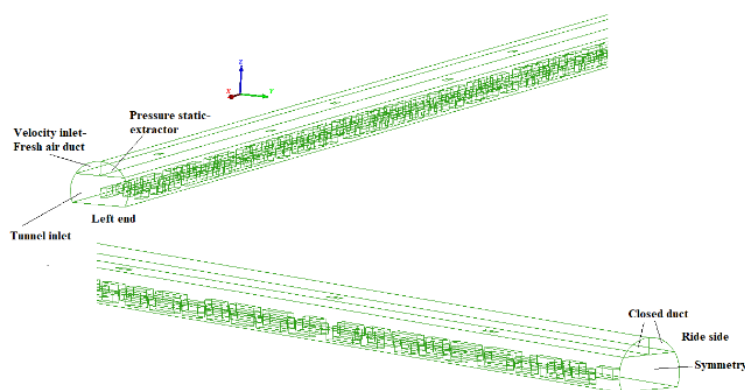


Figure 30: Boundary locations

The details of the boundary conditions assigned are tabulated in table below

Table 26 : Boundary conditions

Location	Boundary condition type	Assigned value
Fresh air duct: left side surface	Velocity inlet	$u = 13.04 \text{ m/s}$
Tunnel inlet	Velocity inlet	$u = 1 \text{ m/s}$
Extractor air duct: left side surface	Pressure static	$P=101325 \text{ Pa}$
Tunnel right side surface	Symmetry	
Right side surfaces of the duct	No-slip adiabatic walls	
Tunnel bottom surface	No-slip adiabatic wall with emission	$\text{CO}=8.09\text{e-}008 \text{ kg/m}^2\text{s}$, $\text{NO}_2= 8.65\text{e-}009 \text{ kg/m}^2\text{s}$, $\text{PM}= 8.32\text{e-}007 \text{ 1/s}$

2.6.1.5 Initial Conditions

The entire tunnel section is initialised with 101325 bar pressure and 300 °C temperature. The initial velocity is set to 0.





2.6.2 Result analysis

In this section, for the normal ventilation scenario, the air flow pattern, pollutant emissions and their extraction from the extractor duct are discussed.

2.6.2.1 Sections

The following sections are taken for plotting the variables.

1. Section 1: XZ, at $Y = -2.7$ m (vertical plane passing through Exhaust Duct damper)
2. Section 2: XZ, at $Y = 3$ m (vertical plane passing through Fresh Air Duct openings)
3. Section 3: XY, at $Z = 5.7$ m (horizontal plane passing through the fans)
4. Section 4: XY, at $Z = 1.7$ m (horizontal plane at an average height location for human)

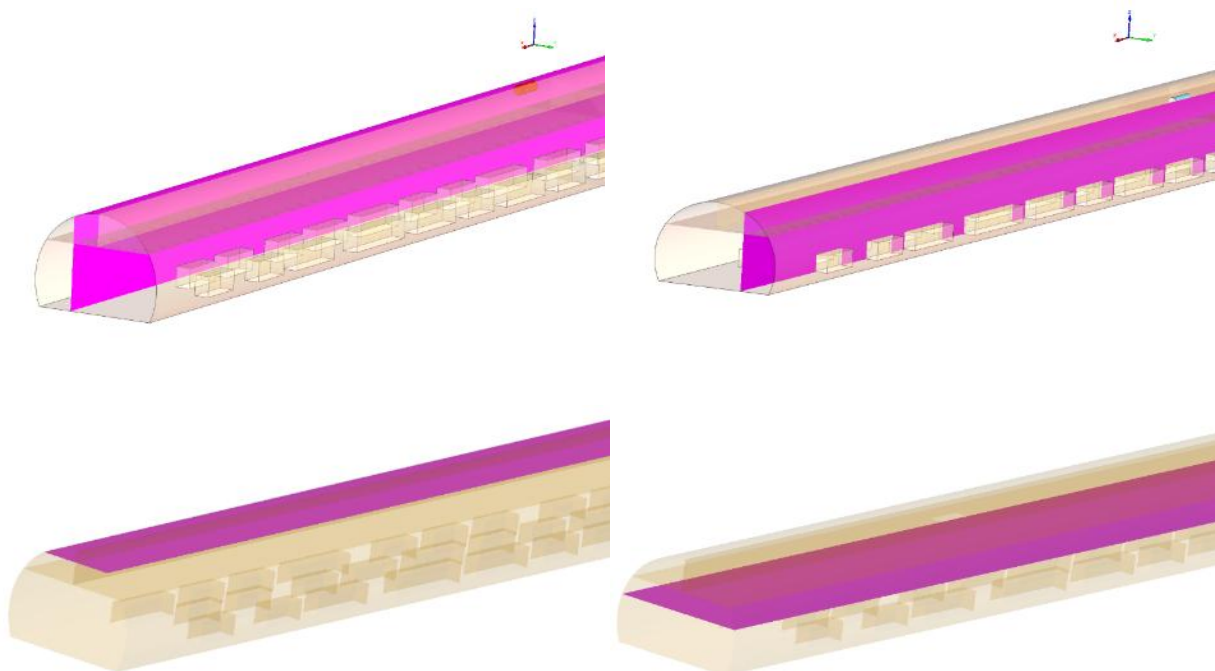


Figure 31: Different sections

2.6.2.2 Flow results: Section 1

2.6.2.2.1 Velocity vectors:

Velocity vector plots on Section 1, passing through the centre of the fresh air openings is shown in figure 32 below. This is zoomed view showing two fresh openings. The flow direction through openings is observed to be in the direction of vehicular motions as well as in downward direction to enhance the flow mixing and dilute the pollutants emitted inside vehicular passage.

The air flow is observed to be sufficiently reaching towards the passages between the vehicles as shown in figure 33.

The similar flow pattern is observed for other openings also.

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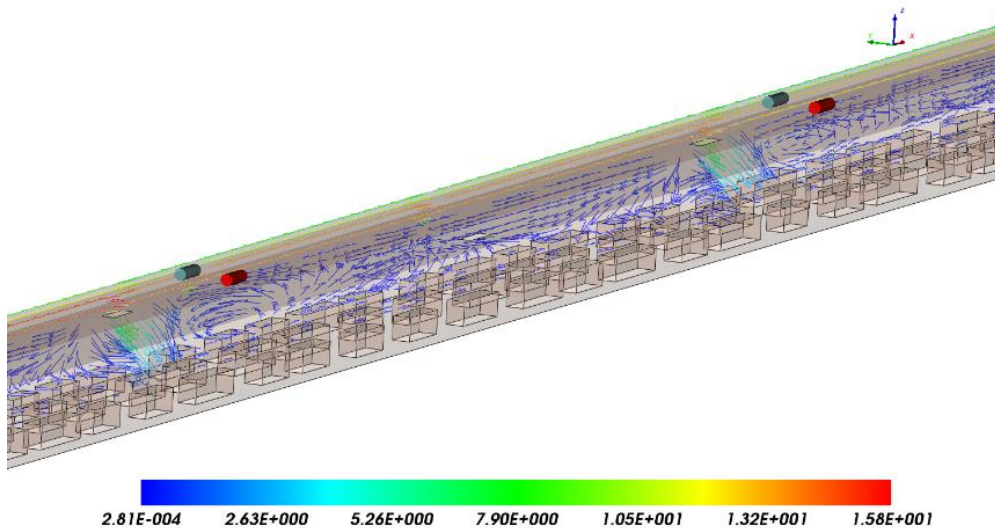


Figure 32: Zoomed velocity Profile on a Section1, passing through fresh air duct opening

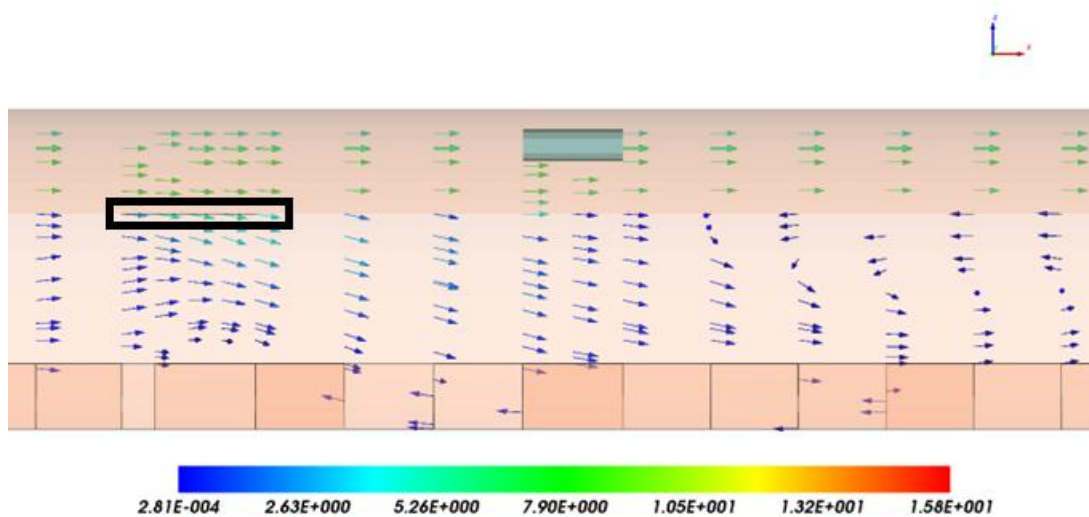


Figure 33: Zoomed velocity profile on Section 1 (Tunnel Side View)

2.6.2.2.2 Speed and pressure contour plots:

The variation of flow speed and pressure across the ducts and vehicular passage of the tunnel are shown in figure 34 and 35 respectively. The average flow velocity coming through the different openings is of the order of 4-6 m/s. The maximum pressure is observed to be towards the right end of the tunnel where ducts are closed.

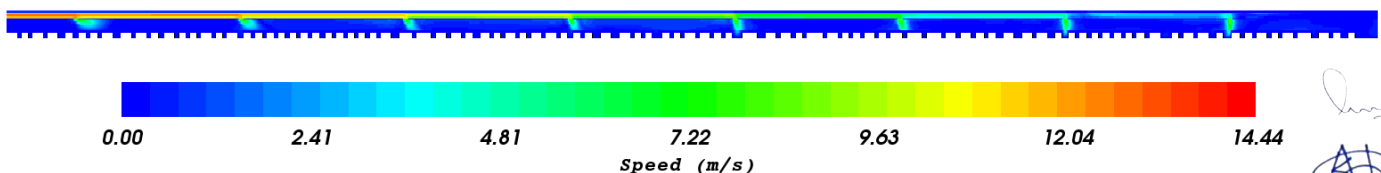


Figure 34: Speed contour plot (Tunnel Side View)

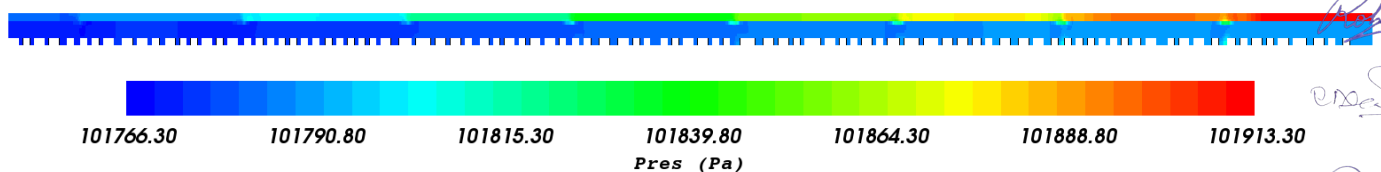


Figure 35: Pressure contour plot (Tunnel Side View)





2.6.2.3 Flow results: Section 2

2.6.2.3.1 Velocity vectors:

The air flow pattern through the extractor openings is shown in figure below 36 through the velocity vectors plotted on Section 2. Only two extractors are highlighted. These extractors are observed to be efficiently allowing the air to pass through it from both sides of it.

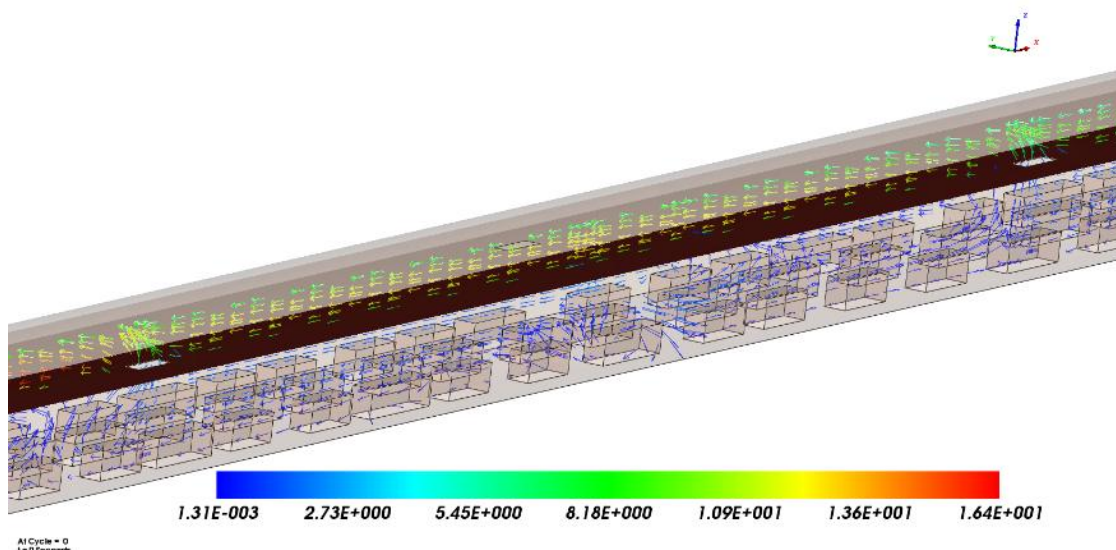


Figure 36: Zoomed view of the velocity vectors on Section 2, passing through extractor openings

The zoomed view of the flow pattern through one of the extractors is shown in figure below

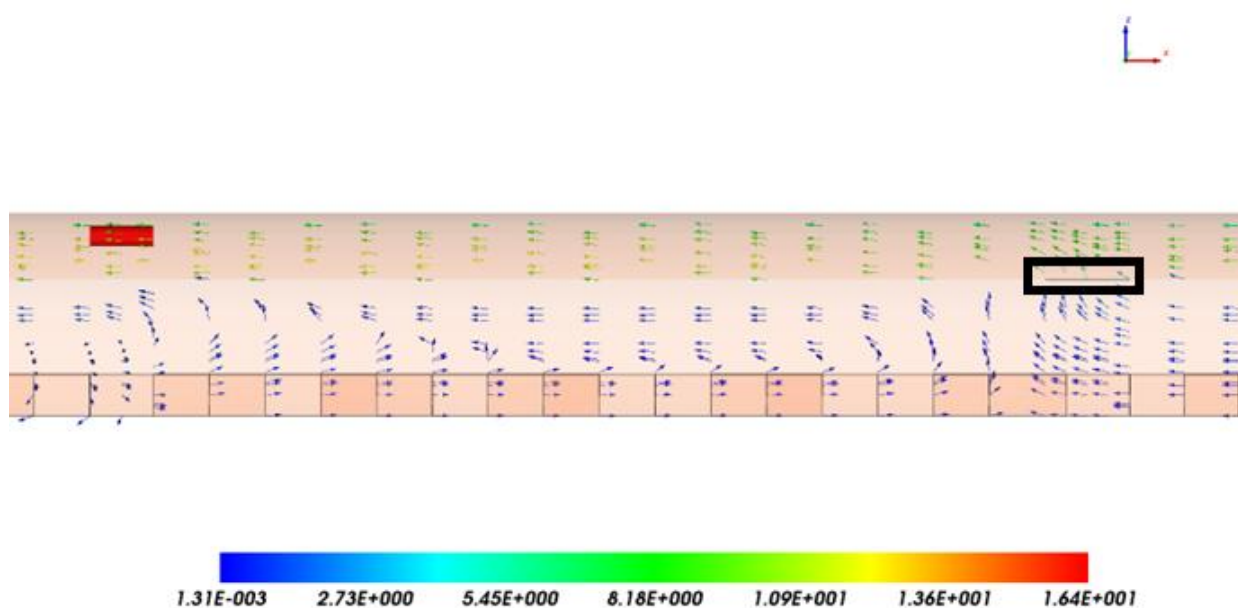


Figure 37: Zoomed view of the velocity vectors on Section 2 (Tunnel Size View)

2.6.2.4 Flow results: Section 3

2.6.2.4.1 Velocity vectors:

The fans are placed inside the duct to maintain the flow momentum throughout the duct length. The typical zoomed flow structure around the fans is shown in figure below by displaying the velocity vectors plotted on Section 3, passing through it.

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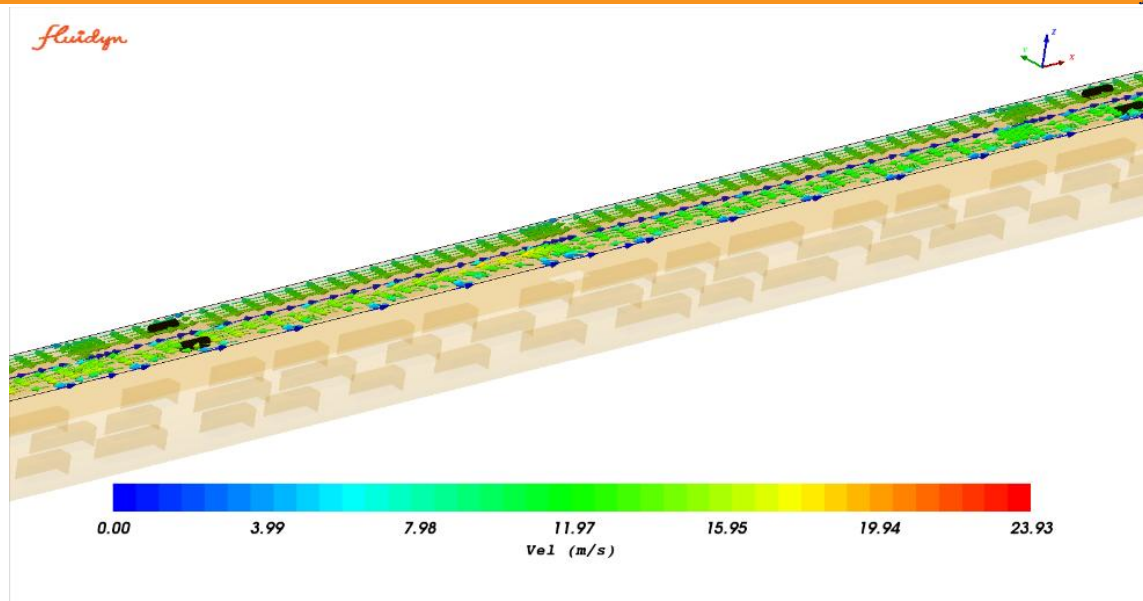


Figure 38: Zoomed velocity vector plot on Section 3, passing through fans

2.6.2.5 Pollutant emissions

2.6.2.5.1 Pollutant distribution:

Figures 39 to 41 show the contour plots of mass fractions of the CO, NO_x and extinction coefficient for PM plotted on Section 4 located at height of 1.7 m. The maximum values are set to the admissible values, which are 70 ppm, 1 ppm and 0.003 m⁻¹ for CO, NO_x and PM (particulate matter) respectively.

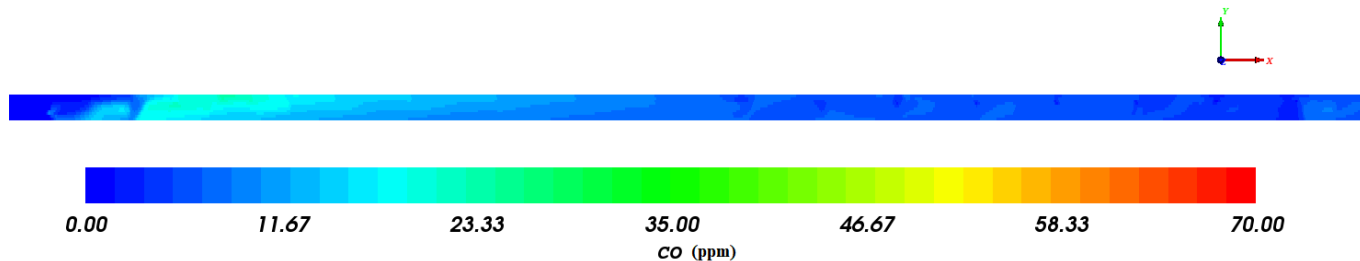


Figure 39: CO contour plot on Section 4

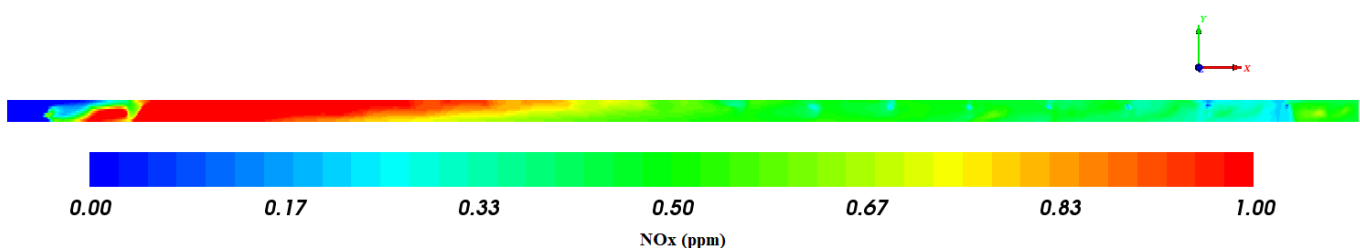


Figure 40: NO_x contour plot on Section 4

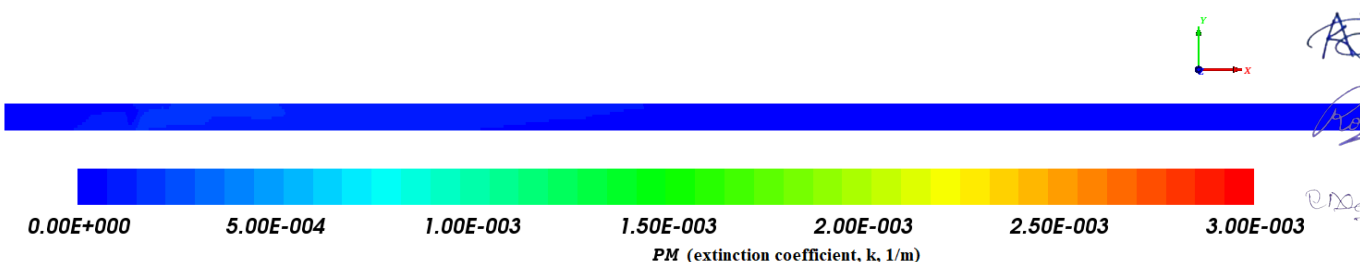


Figure 41: Extinction coefficient contour plot on Section 4





As shown in figures, 39 and 41, the proposed fully transverse design maintains the CO and PM levels and air quality inside the tunnel to admissible levels. It is important to note that, the designed fresh gas flow rate corresponds to the average NO_x emission. In order to further investigate the NO_x levels inside the tunnel, the contour plots of mass fraction of NO_x are plotted on different vertical sections created along the length of the tunnel. These are shown in figure 42

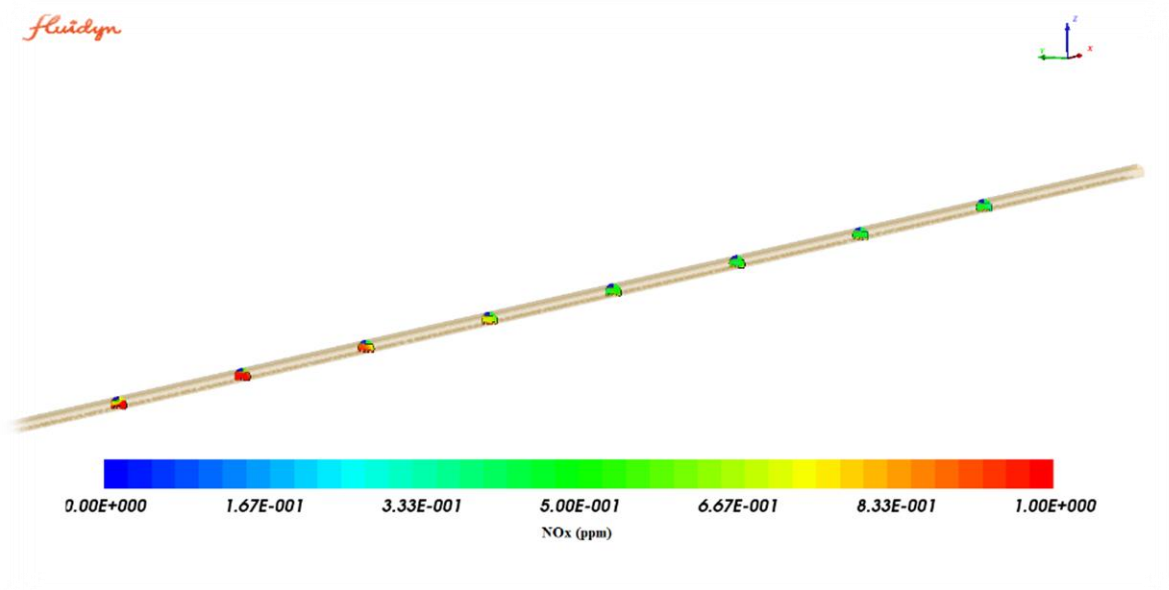


Figure 42: CO contour plots along axial direction

The average values calculated along these planes are tabulated in following table 27.

Table 27 : Average NO_x values along the tunnel length

YZ Section location from tunnel end	Average NO _x values (ppm)
X1=200 m	0.98
X2=400 m	0.96
X3=600 m	0.91
X4=800 m	0.89
X5=1000 m	0.66
X6=1200 m	0.64
X7=1400 m	0.63
X8=1600 m	0.63
X9=1800 m	0.59

So, barring to the inlet region of the tunnel, the average ppm values of NO_x are well below 1 ppm admissible value. It is important to note that, the tunnel flow can dilute NO_x at inlet, therefore these inlet values are less focussed.

It clearly indicates that, the average value remains below 1 ppm for NO_x. Therefore, the proposed fully transverse ventilation design is observed to be sufficient for the normal operation inside the tunnel. Now in the next phase the same design is evaluated for the fire scenario.

2.7 PHASE 2: Fire simulation

2.7.1 Present section includes the description of geometry modelling, mesh structure, numerical inputs and results obtained for the fire scenario

The heat release rate and the design fire curve depend on the probable sources of fire. According to IRC-SP91-20192 (Section 5.9.1) the range of maximum heat release rate is 1.5-300 MW. As per the proposed design, the heat release rate of 30 MW for a duration of 10 minutes is chosen for the simulation purpose.

The tunnel geometry and mesh structure remain the same as used in the natural operation case in the previous phase.





2.7.2 Numerical parameters

For the fire simulation the operating medium is considered the gas mixture included with species CO₂, H₂O, N₂, and AIR. The fluid material properties considered are given in the following table.

Table 28 : Fluid material properties

Fluid Material	Molecular Weight	Viscosity, Pa-s	Density, kg/m ³
CO ₂	44	1.49e-05	Ideal gas law
H ₂ O	18	9.868e-06	Ideal gas law
N ₂	28	1.757e-05	Ideal gas law
Air	28.97	1.71e-05	Ideal gas law

The transient simulation is run until the smoke is removed from the tunnel completely. The turbulence is modelled using standard k-ε model. Pressure velocity coupling is realized through the SIMPLEC algorithm and first order upwind discretization scheme is as convection scheme.

2.7.3 Boundary conditions

Unlike to the Phase 1, for fire simulation purpose, the full tunnel section is considered, the vehicle direction is from left to right end.

The designed fresh air flow rate required to maintain the admissible air quality during the normal operation is 163 m³/s. This is realized by assigning the velocity boundary condition at the left and side surface of the fresh air ducts. In order to maintain the same momentum corresponding to this flow rate, the 17 fans are assigned in each part of the full tunnel section, with velocity equivalent to the distributed flow rate.

The extractor duct fans are operated with the full capacity equal to the designed value 90000 m³/h. This is achieved by assigning the volume flow rate to the left and right-side faces of the extractor ducts. The tunnel inlet and right-side surfaces are assigned with the pressure static boundary condition.

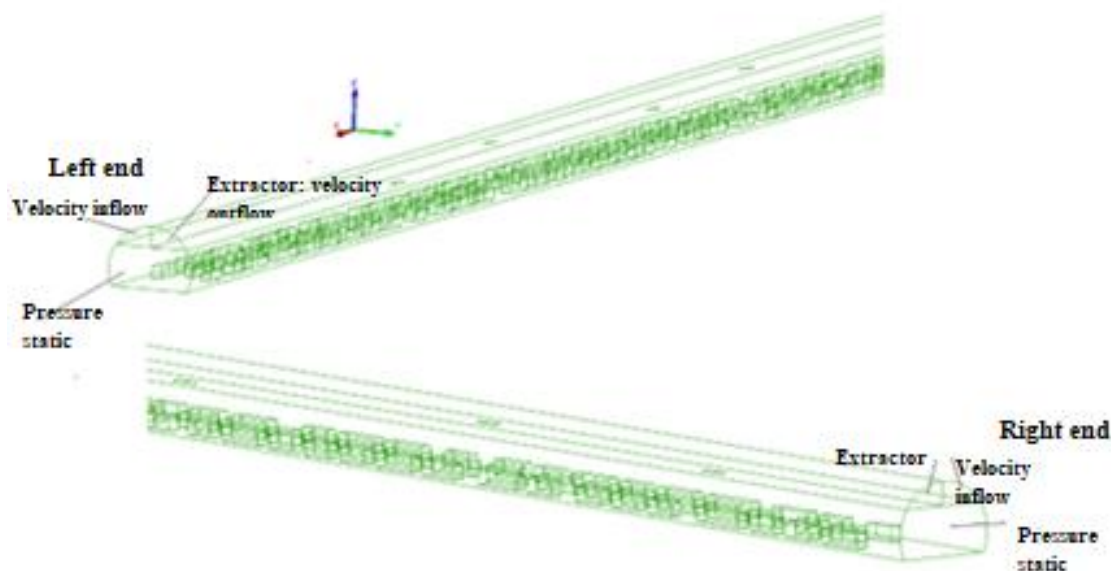


Figure 43: Boundary surfaces

The fire source is located at the central position of the tunnel section. It is defined as the volume source with volume as 30 m³. This is shown in following figure:

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Figure 44: Fire location and closed openings

The details of the boundary conditions assigned are tabulated in table below:

Table 29 : Boundary conditions: Fire scenario

Location	Boundary condition type	Assigned value
Fresh air duct: left side surface	Velocity inlet	$u = 13.04 \text{ m/s}$
Tunnel inlet and right-side surface	Pressure static	$P = 101325 \text{ Pa}$
Extractor air duct: left and right-side surface	Velocity outflow	$Q = 425 \text{ m}^3/\text{s}$
Right side surfaces of the duct	No-slip adiabatic walls	
Heat source	Fire inputs	Heat source= 30 MW, $t = 10 \text{ min}$

2.7.4 Initial Conditions

The transient case is initialized with the steady state flow results obtained during the natural operation case.

2.7.5 Result analysis

The fire simulation results are discussed mainly in terms of the distribution of smoke (CO_2 , CO), and temperature variations. The extracted mass of the CO and CO_2 are also monitored at the extractor duct outlets over the period of time.

2.7.6 Mass fraction and temperature contour plots

Figure 45 and 46 show the smoke spread over the period of time in terms of the contour plots of the mass fractions of the CO and CO_2 . These plots are plotted on Section 2 passing through the extractor openings.

The maximum limit of the mass fraction for CO plots is set to the admissible value of 200 ppm.

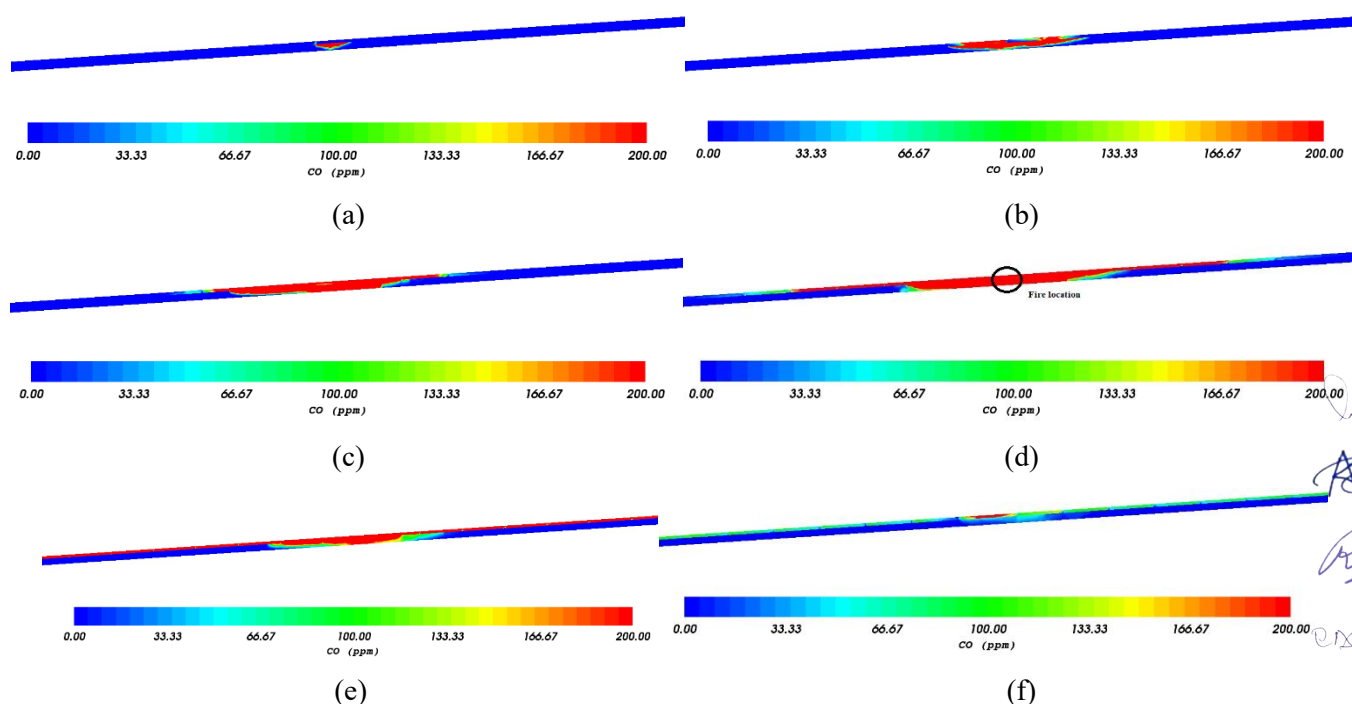


Figure 45: CO mass fraction, zoomed views within the limit of 1.5 km downstream to fire location (a) 100 sec, (b) 300 sec, (c) 600 sec, (d) 1000 sec, (e) 1500 sec, (f) 2500 sec



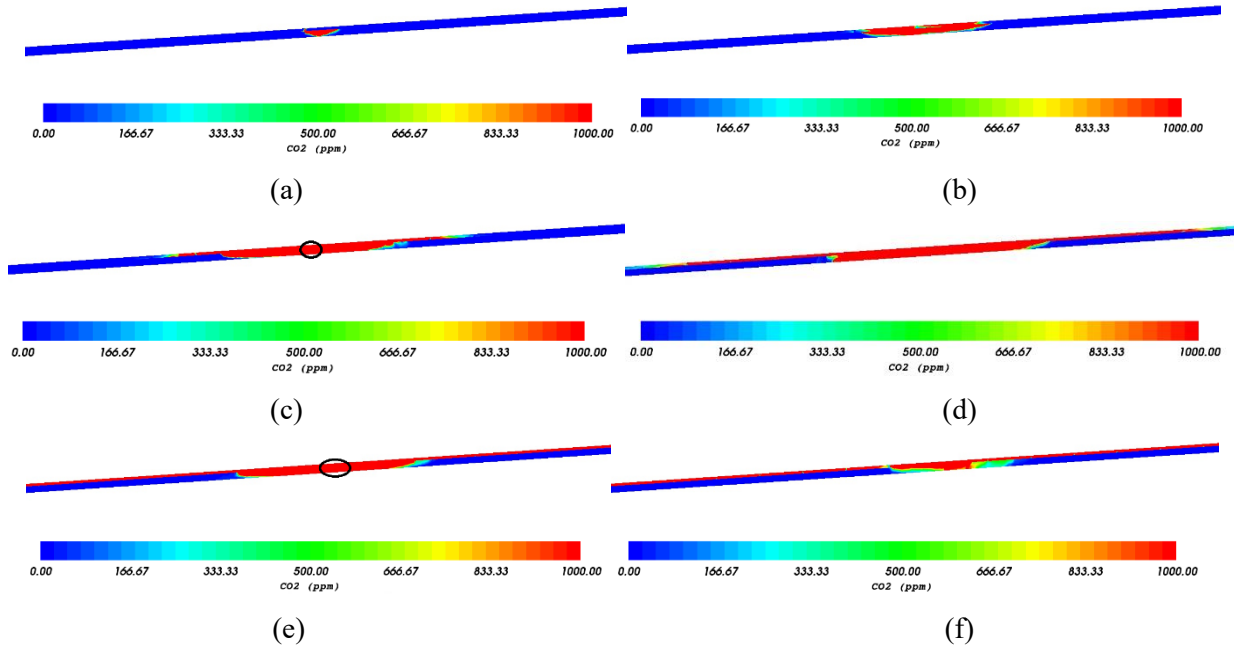


Figure 46: CO₂ mass fraction, zoomed views within the limit of 1.5 km downstream to fire location (a) 100 sec, (b) 300 sec, (c) 600 sec, (d) 1000 sec, (e) 1500 sec, (f) 2500 sec

As seen in this figure 45, as the extractors operate with full capacity, the smoke is prevented from spreading towards the tunnel inlet side. However, it spreads towards the direction of vehicular motion slightly more.

For more understanding of the smoke propagation and its removal process, the iso-surface plots of the CO mass fraction are plotted for two different times, as shown in following figure 47.

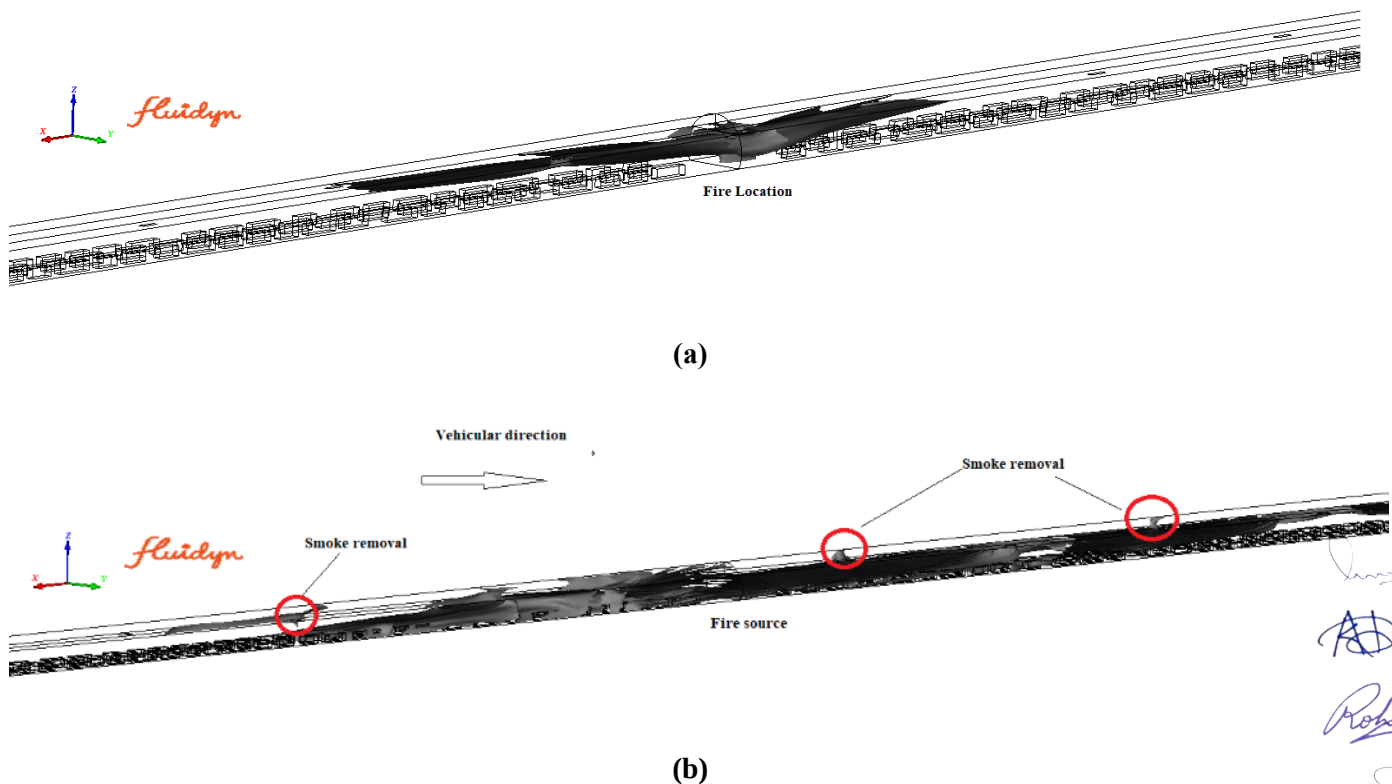


Figure 47: CO iso-surface contours, (a) 100 sec, (b) 1000 sec

The temperature contour plots plotted on Section 2 at different times are also shown in following figure 48



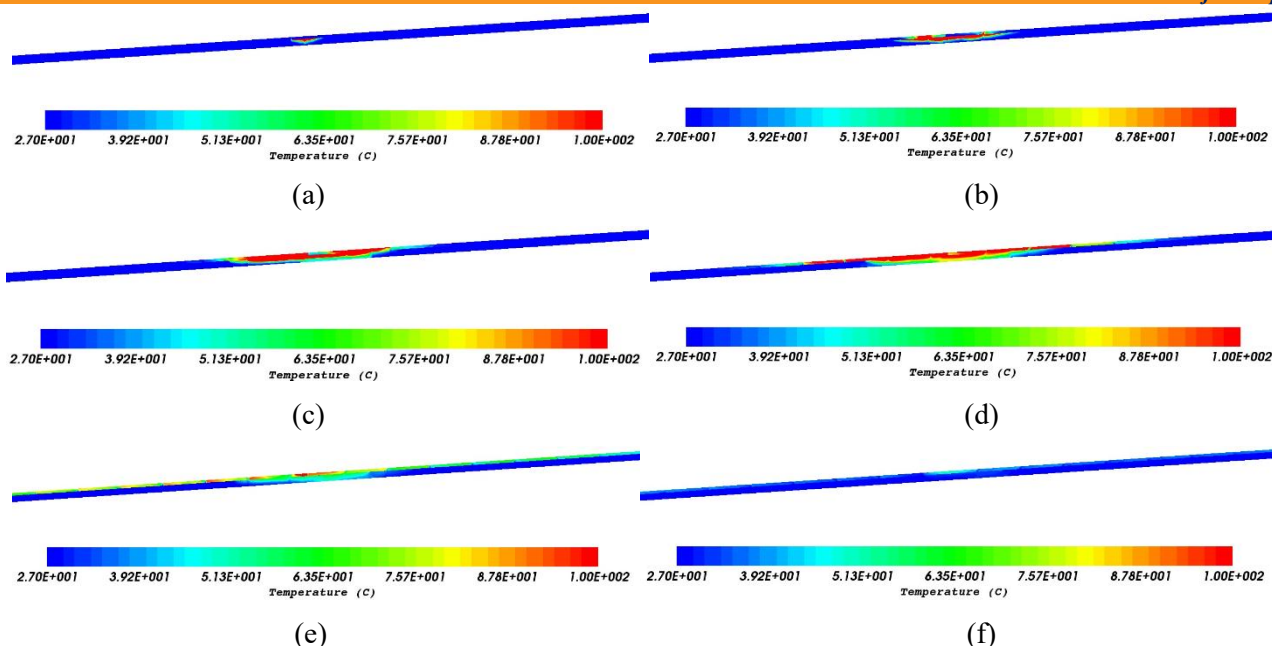


Figure 48: Temperature contours, zoomed views within the limit of 1.5 km downstream to fire location (a) 100 sec, (b) 300 sec, (c) 600 sec, (d) 1000 sec, (e) 1500 sec, (f) 2500 sec

2.7.7 CO and CO₂ extracted mass:

The total mass of the CO and CO₂ varying inside the tunnel section with time is given in the plot in figure 49. As seen through this figure, the extractors continuously remove the increased mass of the CO and CO₂. Once the fire duration, 10 min, is over, the remaining mass of the CO and CO₂ is removed within close to next 30 min. time.

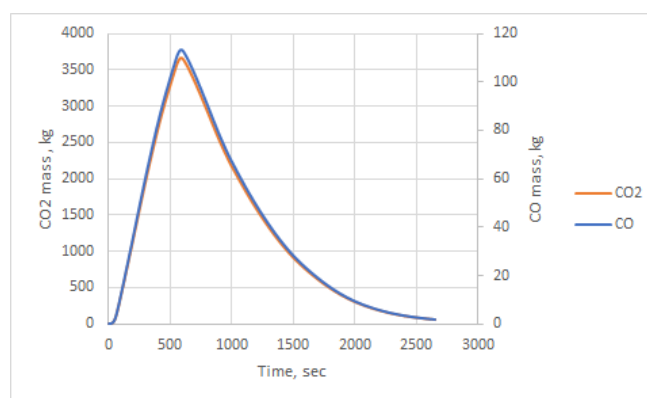


Figure 49: Extracted CO and CO₂ mass

2.7.8 Evacuation of passengers:

The proposed fully transverse ventilation design doesn't allow the smoke to propagate towards the tunnel inlet.

The smoke, where the levels are measured with the admissible values of CO, is observed to be spreading maximum to a distance of 500 m (250 m each side of the fire) within a time span of 25 min. Afterwards, it is observed to be removed through extractors and brought to the level within admissible values within next 15 min. In overall, the fire control has taken place within 40 min. overall.

It is also important to note here that, the effect of other fire containing measures such as the use of fire extinguishers is not considered during this simulation, which surely can minimize the fire spreading effect.

As the ventilation system does not allow the smoke propagation upstream of fire, it can facilitate the evacuation in this direction. The immediate cross passages upstream to the fire location can be used for the same.





It is also suggested to avoid opening of the nearest cross passage downstream to fire location and the ones next to it can be used for evacuations.

2.7.9 Conclusions

The CFD analysis of the proposed fully transverse ventilation design is carried out to verify its efficiency during the normal operation and fire scenarios. The designed values of fresh air flow rate and fire loads are considered for the simulations. The tunnel air flow quality and smoke removal is addressed by providing appropriate fresh air and extractor openings, which are placed in staggered manner. Following conclusions are drawn from these studies.

- The proposed fully transverse ventilation design of the tunnel is found to be sufficiently distributing and passing the fresh gas inside the vehicular passage and also working efficiently during the fire scenario
- The proposed design is observed to be maintaining the air quality inside the vehicular passage to the admissible levels of CO, NOX and PM during normal operation of the tunnel
- The ventilation design is observed to be preventing the smoke propagation towards the tunnel entry side.
- This design observed to be removing the smoke within the 40 min of its operations where extractor duct fans are operated with full capacity. Additionally, the prevention of smoke spreading towards the tunnel inlet can facilitate the safe evacuation upstream to fire location.

2.7.10 References

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3. Maevski, I, Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels, NCHRP Research Report 836, 2017.
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8. Directive 2004/54/EC: Minimum safety requirements for tunnels in the Trans-European Road Network

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