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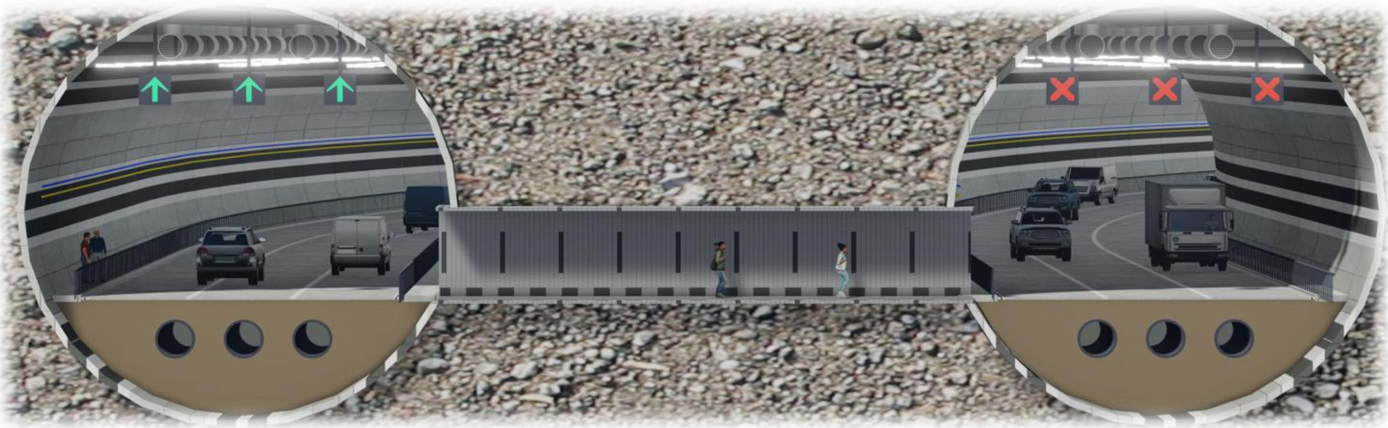
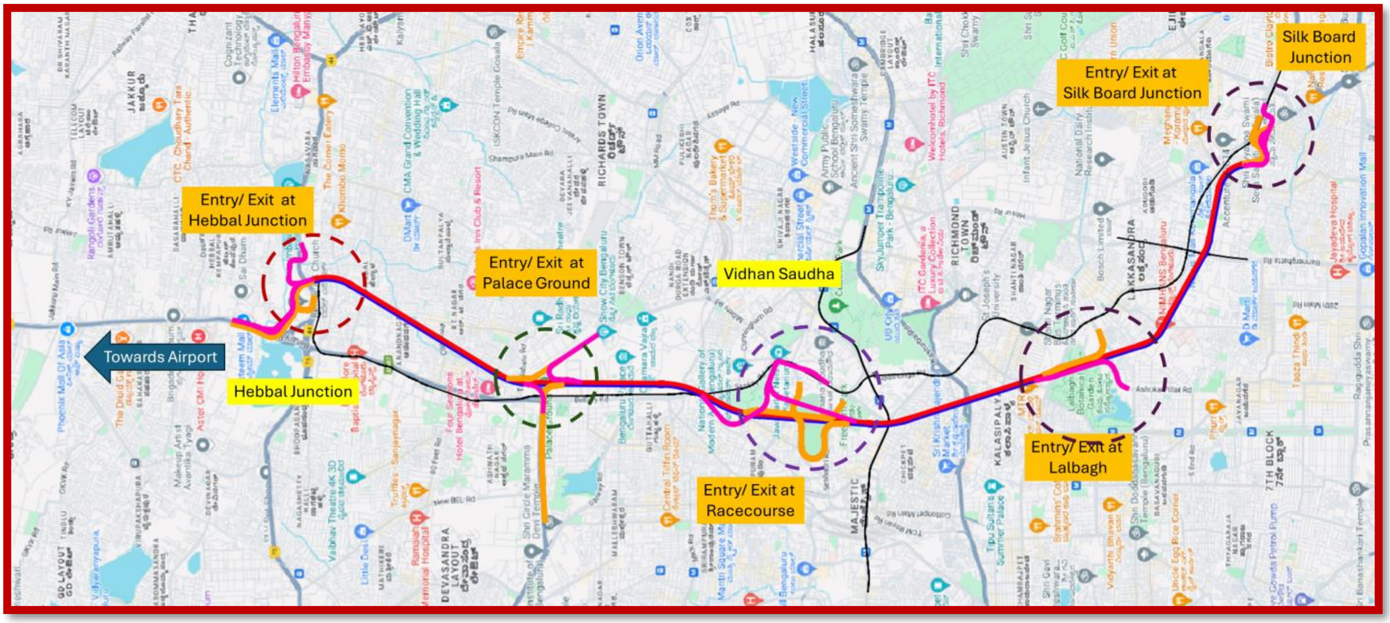


CONSULTANCY SERVICES FOR PREPARATION OF DPR FOR THE WORK OF CONSTRUCTION OF UNDERGROUND VEHICULAR TUNNEL FROM HEBBAL ESTEEM MALL JUNCTION TO SILK BOARD KSRP JUNCTION



DRAFT DETAILED PROJECT REPORT

VOLUME - II D

VENTILATION DESIGN REPORT

September 2024

RODIC CONSULTANTS PVT. LTD

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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. Read the original tender document issued by BBMP for the DPR and the work order from Rodic.
2. Divide the tunnel into different sections. Decide the number and locations of ventilation stations available.
3. Design the tunnel cross sections at different locations. For each section:
   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, NOx 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.
      i. For longitudinal system: tunnel friction losses, entry losses, traffic effect, wind resistance

and vertical shaft friction losses.

ii. For transverse (in addition to the losses mentioned for longitudinal system):

1. Decide the number of ventilation blocks between two ventilation stations.
2. Decide the layout of the separate ducts for fresh and exhaust air based on the total required airflow rate for the block and a maximum duct velocity of 10-15 m/s.
3. Calculate the duct pressure losses considering a variable flow rate along the length of the duct to provide uniform air supply to the tunnel from the duct for normal operations.
4. Calculate pressure drop in tunnel each section using the local emission rates.
5. Decide the number of openings between the ducts and the tunnel and the pressure losses due to them.
6. Estimate the pressure drop adding all the abovementioned losses.

d. Calculate the number of fans and the distance between fans based on the pressure drop.

e. Do a network analysis using the fan data and verify whether the required flow rates can be obtained in all the lines (optional).

f. Do a 1D network analysis (optional)

g. Do 3D simulations of selected regions to check the quality of air flow patterns.

h. Choose the fire curve and heat release rate

i. Estimate the tunnel air flow required for efficient smoke removal.

j. Check if the maximum capacity and the arrangement of the fans chosen based on pollutant dilution are sufficient to provide the air flow rate and pattern required for the 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 duct layout and control to satisfy the smoke removal requirement.

k. Decide the exhaust and intake locations and directions to avoid mixing of both the air streams in the nearby ambient.

l. Decide the firefighting systems required.

i. Sensors

ii. Sprinklers

iii. Fire extinguishers

iv. Fire hoses

v. Back up passive oxygen supplies

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.

1.3 Layout of the Proposed Tunnel

Information on the proposed tunnel as given in the request for proposal document (BBMP, 2024) and the work order (Rodic, 2024) are given in this section.

It has two separate tubes throughout. Each tunnel has an inside diameter of 13.5 m. In addition, there are four entry tunnels and four exit tunnels. Figure 1 and Figure 2 show the general layout of the tunnel system with the qualitative depiction of some of the components, such as main tubes, exit and entry points, cross passages, and extraction points. Though Table 1 gives the approximate stretches, the locations of actual exits and entry points for both sides and ventilation stations as measured from the supplied kmz file, are given in Table 1, Table 2, Table 3 and Table 4.

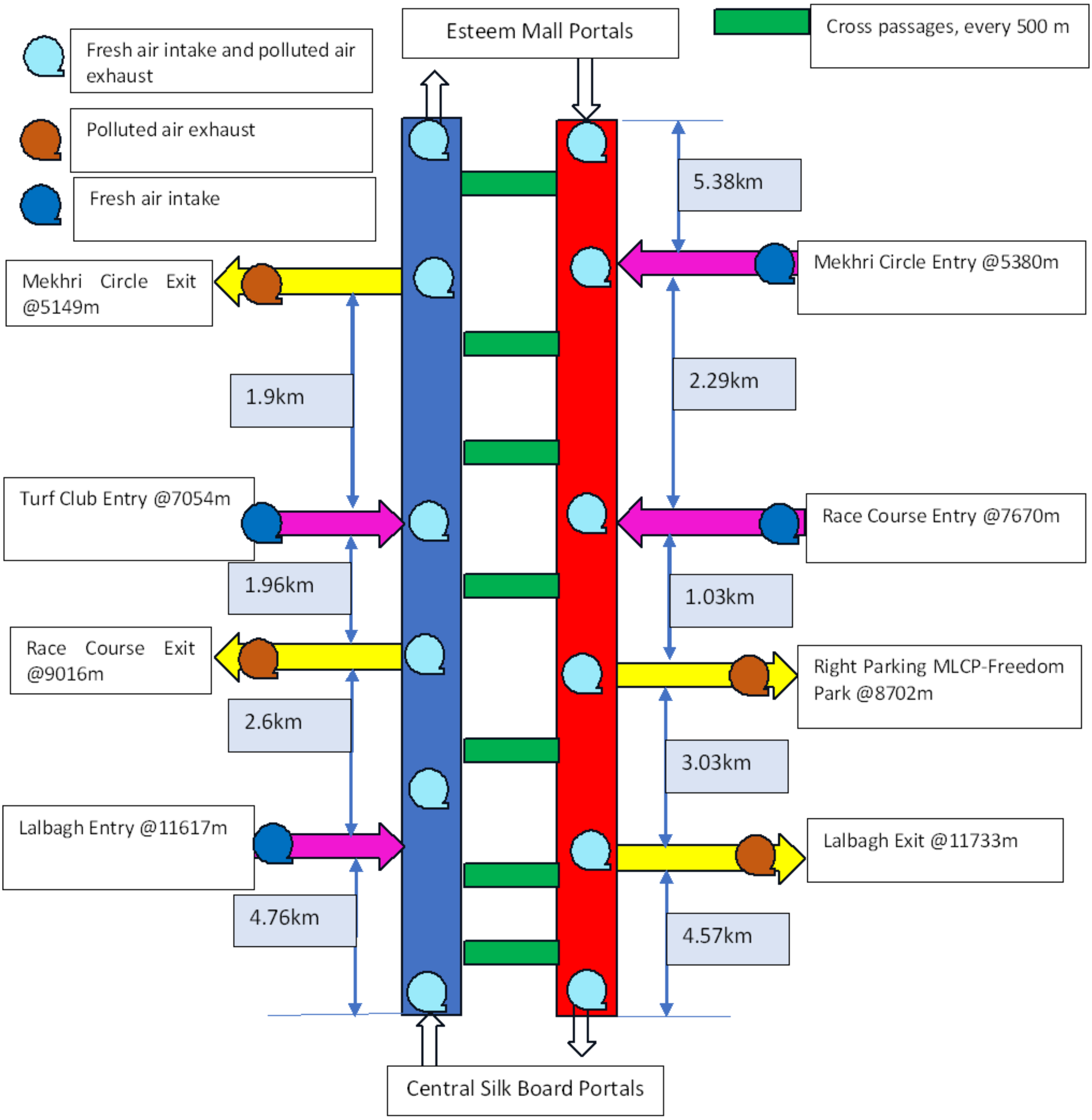

Figure 1: General layout of the proposed tunnel (not to the scale)

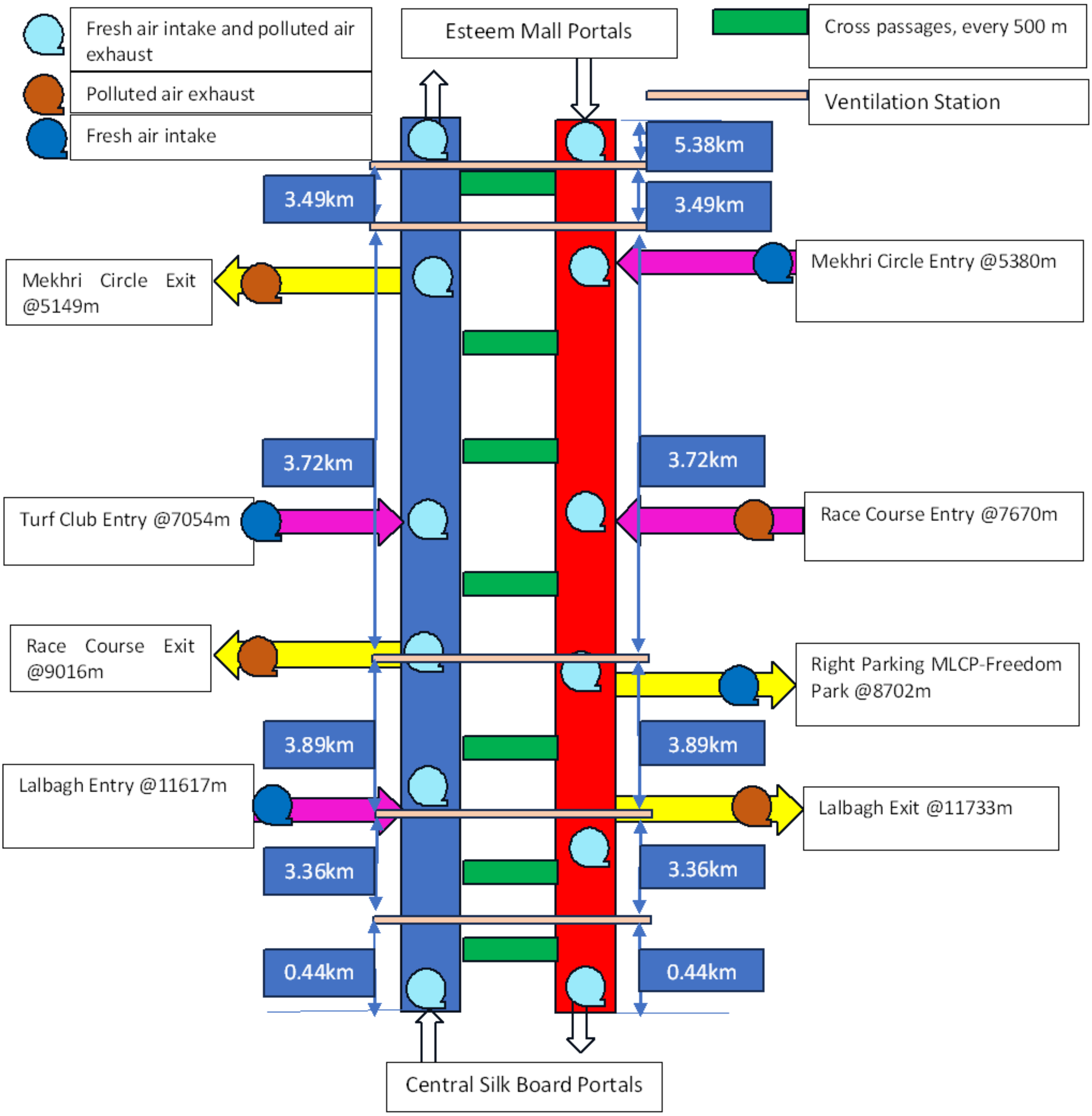

Figure 2: General layout of the proposed tunnel with Ventilation Stations (not to the scale)

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

Name	Entry/Exit	Distance from Esteem Mall, m	Length, m
Esteem Mall	Entry	0	0
Mekhri Circle	Entry	5380	5380
Race Course Entry	Entry	7670	2290
Right Parking MLCP-Freedom Park	Exit	8702	1031

Name	Entry/Exit	Distance from Esteem Mall, m	Length, m
Lalbagh	Exit	11733	3031
CSB	Exit	16303	4570

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

Name	Entry/Exit	Distance from Esteem Mall, m	Length, m
Esteem Mall	Exit	0	0
Mekhri Circle	Exit	5149	5149
Turf Club	Entry	7054	1905
Race Course	Exit	9016	1961
Lalbagh	Entry	11617	2601
CSB	Entry	16374	4757

Table 3 : Ventilation Sections (VS0 to VS6 are the ventilations stations)

Ventilation Sections	Distance from Esteem Mall to the farthest station, m	Length of section, m
VS0-VS1	1477	1477
VS1-VS2	4964	3487
VS2-VS3	8684	3720
VS3-VS4	12572	3887
VS4-VS5	15934	3362

Table 4 : Entry and Exit Tunnels for Sections between Ventilation Stations

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

1.4 Tunnel Cross Section

Figure 3 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 m^2.

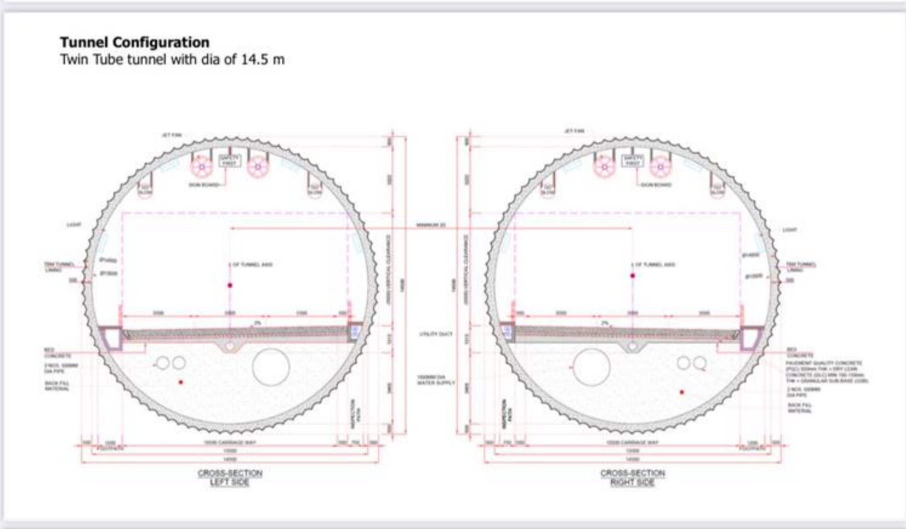

Figure 3: Tunnel cross-section

1.5 General Design of the Ventilation System

Figure 1 shows the schematic of the tunnel system from the ventilation point of view. Portion between two consecutive ventilation stations is considered as a section. Fresh air intake and polluted air exhaust are placed only at the ventilation stations. The entry and exit tunnels will have longitudinal systems. In these tunnels, the air flow under normal operating conditions will be in the direction of traffic. Main tunnels will have a longitudinal system and/or a transverse system depending on the length of the sections (IRC, 2019). At the points of extraction flow will be transverse through the vertical shafts and ducts with dampers at the roof of the tunnel. Hence, the complete system is a combination of longitudinal and partially-transverse systems. The main tunnels will be connected through cross passages at an interval of 500m 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).

1.6 Guidelines

Following codes or guidelines with their updated versions, if any, will be considered for ventilation design purposes.

Table 5 : Guidelines

Sr. No.	Code	Details
1	IRC: SP-91-2019	Guidelines for Road Tunnels
2	PIARC: 05-02-B, 1995	Vehicle Emissions, Air Demand, Environment, Longitudinal Ventilation
3	PIARC: 05.05.B, 1999	Fire and Smoke Control in Road Tunnels
4	PIARC: 2017R01EN, 2017	Design Fire Characteristics for Road Tunnels
5	PIARC: 2019R02EN, 2019	Road Tunnels: Vehicle Emissions and Air Demand for Ventilation
6	NFPA 502	Standard for Road Tunnels, Bridges, and Other Limited Access Highways
7	NFPA 14	Standard for the Installation of Standpipe and Hose Systems
8	Directive 2004/54/EC	Minimum safety requirements for tunnels in the Trans-European Road Network

1.7 Type of ventilation system

1.7.1 Natural or Mechanical Systems

There are two broad types of ventilation systems:

1. Natural ventilation:
2. Mechanical ventilation

In some cases, natural ventilation due to piston effect of the moving vehicles is sufficient to provide the sufficient air quality. However, the need for a mechanical ventilation system has to be assessed based on various factors such as length of the tunnel, possibility of congestion, traffic type (bi-directional or uni-directional), type of vehicles, and possibility of fire. Table 6 contains the general characteristics of the proposed tunnel. Based on this and the guidelines of IRC SP91-2019 a mechanical ventilation system is chosen for all the sections of the tunnel.

Table 6 : Tunnel General Characteristics

Factor	Remarks
Length of the tunnel	Four sections with lengths ranging from 2.8 km to 5.72 km.
Possibility of congestion	Yes
Traffic type (bi- or uni-directional)	Two uni-directional tubes interconnected through cross passages
Type of vehicles	Mix of passenger cars, LCV, Buses and HGVs.
Possibility of fire	Yes

1.7.2 Choice of Mechanical System

The mechanical ventilation systems may be classified into the following groups:

1. Longitudinal
2. Massive point or point-flow extraction
3. Fully transverse
4. Semi-transverse and reversible semi-transverse
5. Partial transverse

IRC SP91 suggest semi-transverse systems for tunnels longer than 2km with high traffic density. The proposed tunnel falls into this category. Also, considering the possibility of fire, a reversible transverse system may be suitable, at least for the longer sections. However, there are precedents in using a longitudinal system in similarly long tunnels (MCRP). So, design airflow rate and fan calculations are done for a longitudinal system and a transverse system are done. Then the longitudinal system is analysed for smoke stratification in one of the sections. If it is not found to be sufficient then the transverse system will be recommended based on other constraints.

References:

1. DPR MCRP
2. IRC SP91-2019
3. PIARC, Road Tunnels Manual: Strategy and General Design – Ventilation Concepts, Version 2, 2019.

1.8 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

1.8.1 Estimation of Pollutant Load

As per PIARC guidelines, the emissions in terms of CO, NOx (sum of NO and NO2) and particulate matters 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

The guidelines or reference codes selected to estimate these pollutant loads are as follows:

- Indian road congress, IRC SP 91-2019
- World Road Association, PIARC: "Road Tunnels: Vehicle Emissions and Air Demand for Ventilation", 2019, section 2.3
- World Road Association, PIARC: 05.02.B "Road Tunnels: Emissions, Environment, Ventilation", 1996

1.8.2 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.

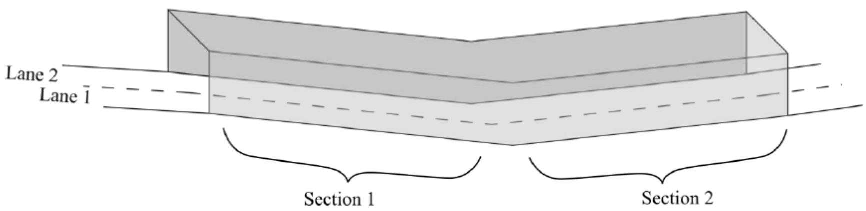

Figure 4: Schematic of sections selected based on constant slope/gradient

Individual sections are selected based on the ventilation station location details given in Section 1.3.

1.8.3 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)
- 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 mas of the HGV vehicle
- Pollutant concentration in fresh air/ fresh air quality separate estimations will be provided for the CO and NOx 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 5 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 5: Typical emission rate data

For the present design, based on the information received from the traffic analysis, the vehicle composition is 80% PCUs and 20% LCVs. All are assumed to be petrol vehicles.

1.8.4 Estimation of Pollutant Emission Rates

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

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

The maximum emission rates among these are selected for further airflow rate requirement calculations.

All the vehicles are petrol PCUs. Table 7 gives the emission rates estimated for all the sections.

Table 7 : Emission rates (g/h) in different sections for one tunnel

Section	Highest emission rate from different speeds		
	CO	NOx	PM
VS0-VS1	7070	756	73
VS1-VS2	19691	2106	203
VS2-VS3	20046	2145	206
VS3-VS4	20946	2241	215
VS4-VS5	10934	1170	112

1.8.5 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 and operational pollutant values
2) Fresh air requirement estimation

1.8.6 Design 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 provided these values for different pollutants which will be considered are same are given as follows

- Design values for CO emission:

Table 8 : Design values for CO emissions, (IRC, PIARC)

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 NOx:

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. However, following issues will be

- 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 9 : Design values for visibility based on PM emissions, PIARC

Visibility condition	Extinction coefficient K	Length of light beam L with $\frac{I}{I_0} e^{(-KL)} = 20\%$
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

1.8.7 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).

The following reference documents will be used for the same.

1. PIARC Report: "Road Tunnels: Vehicle Emissions and Air Demand for Ventilation", 2019, section 2.2
2. IRC SP 91-2019

The separate estimation of fresh air requirement (m3/h) will be provided based on estimated CO, NOx and PM loads. 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.

1.8.8 Fresh Air Rate Requirements

Based on the pollutant emission rate obtained for parameters given in Table 7, the fresh air rate required for each pollutant is calculated according to PIARC (2019R02EN) guidelines. These values are given in Table 10

Table 10 : Fresh air rates (m^3/s) required to dilute the pollutants in different sections for one tunnel

Section\Speed	Highest airflow rate (m^3/s)		
	CO	NOx	PM
VS0-VS1	20	112	4
VS1-VS2	56	311	11
VS2-VS3	57	317	11
VS3-VS4	59	331	12
VS4-VS5	31	173	6
VS5-VS6	43	240	9

The maximum fresh air rate of 318 m^3/s is required for NOx. So, this is chosen to estimate the pressure drop in the tunnel and decide the number of fans. The tunnel air velocity corresponding to this rate is 3.2 m/s, 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 1-1.5m/s recommended by IRC (Section 5.7 in IRC, 2019). Also, this airflow rate corresponds to approximately 3.2 air change rates, which is in line with the IRC guidelines.

1.8.9 Design of a Ventilation System

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

1.8.10 Ventilation System type

There are mainly two types of ventilation systems exist, natural and mechanical. According to the European directive, a mechanical ventilation system shall be installed in tunnels longer than 1000 m. The guidelines provided in "IRC SP 91-2019" suggests that, the mechanical ventilation system is required for the tunnel lengths/section lengths more than 500 m. As per the Table 1 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 is 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.

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).

- 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.

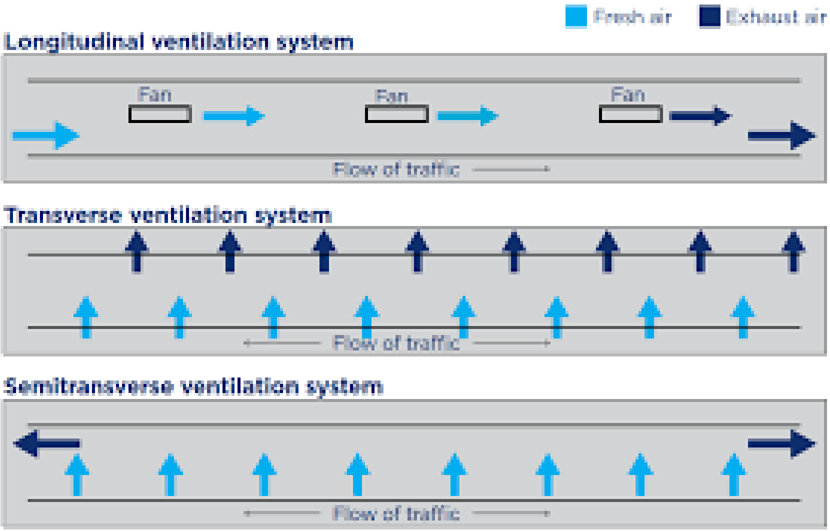

Figure 6: Schematic of different types of ventilation systems

According to IRC-SP91-2019 guidelines semi-transverse system is generally used for tunnels longer than 2000m with high traffic density. However, this selection will have to consider the feasibility of providing shafts for fresh air inflow and polluted air outflow. Also, there are precedents of using longitudinal system even for tunnels longer than 2 km due to the difficulties in providing the ducts and inflow for the transverse or semi-transverse systems.

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. Following reference codes will be considered for the same:

1) IRC: SP:91-2019 Guidelines for Road Tunnels.

2) PIARC: Road Tunnels Manual: Strategy and General Design Version 2 - 01/10/2019 and related documents.

Figure 7 shows an example of ventilation system selection process. Following this, major characteristics of the present tunnel affecting the choice of ventilation system are given in Table 11.

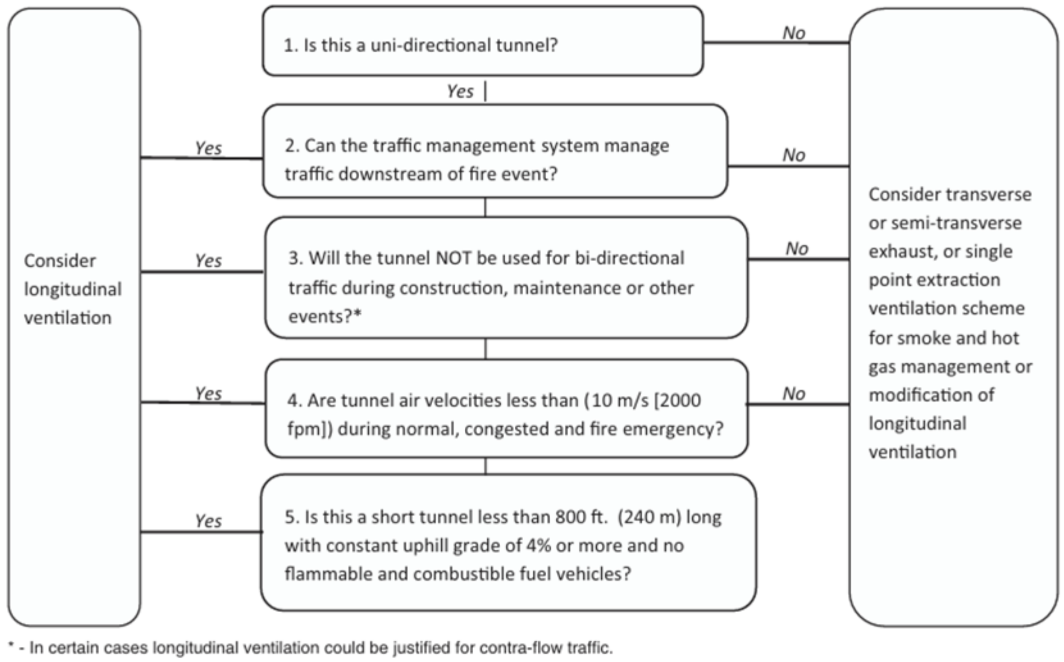

Figure 7: An example of ventilation system selection process (Maevski, 2017)

Table 11 : Characteristics of the current tunnel to choose the ventilation system

Tunnel property	Yes/No
Bi- or Uni-directional	Uni-directional
Expected traffic density	Urban and high density
Traffic management downstream of a fire event	Yes
Will it be used for bi-directional traffic during some events	No
Is tunnel air velocity less than 10 m/s?	Yes (for pollutant removal)

If the tunnel is completely restricted for uni-directional traffic and if the air velocity for a fire event is less than 10 m/s, then a longitudinal system with intermediate shafts for extraction may be considered. However, this has to be finalised after design iterations and verification based on fire scenario simulations.

1.8.11 Design and Dimensioning of the Ventilation System

The design and dimensioning of the ventilation system will be based on following three parameters:

1. Selection of ventilation type based on fresh air requirement
2. Cross-section of the tunnel at different sections
3. Topological constraints

Based on the detailed topological survey, points 2 and 3 will be addressed. Along with this the appropriate guidelines will also be followed for the same based on following references:

1. IRC SP 91-2019
2. PIARC Report: “Road Tunnels: Vehicle Emissions and Air Demand for Ventilation”, 2019, section 2.3

Also, since this is an urban tunnel passing through highly populated areas, the locations of the shafts for the exhaust of the polluted air will have to be decided based on the pollution limits for the overground.

1.8.12 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.

1.8.12.1 Longitudinal System

Table 12 and Table 13 gives the design values arrived at using the highest air flow requirement for all the sections and the fan specifications for the longest section, respectively, for a longitudinal system (Ref: PIARC, 1995).

Table 12 : Longitudinal System Fan Requirement

Section Distance (m)	Total NOx Emission (g/h)	Air Flow Rate (m^3/s)	Pressure Drop	No. of Fans	Total Power (Kw)	Distance b/w Fans (m)
1312	756	112	7	3	38	875
3654	2106	311	146	57	651	129
3720	2145	317	154	60	677	124
3887	2241	331	176	69	779	113
2029	1170	173	26	10	121	406
2817	1624	240	68	26	308	217

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

Parameter	Value	Remarks
Tunnel cross section area, m^2	102	
Area available for air flow, m^2	92	Subtracting the vehicle cross section area
Fresh air rate, m^3/s	331	For NOx
Pressure drop in Tunnel, Pa	176	
Fan flow rate, m^3/h	56000	
Fan area, m2	0.65	
Pressure rise by fan, Pa	2.6	For the tunnel cross-section area
Total number of fans	69	
Distance between fans, m	113	Assuming two fans at one section
Type of fan	Jet fan	
Power, kW	11.3	Per fan (minimum - estimated)

The number of fans given above was calculated without considering the entry losses, wind resistance, vehicle drag and losses due to any additional constructions and bends in the tunnel. This number will be updated after getting the input related to these.

1.8.12.2 Transverse System

Figure 8 shows a possible arrangement of the duct for the 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 8. This will be modified if any improvement in air flow in the tunnel is required. 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 m^2. The total cross-section area is 105 m^2 and the required air flow rate is 323 m^3/s. This results in a maximum velocity of about 26 m/s in the fresh air and exhaust ducts.

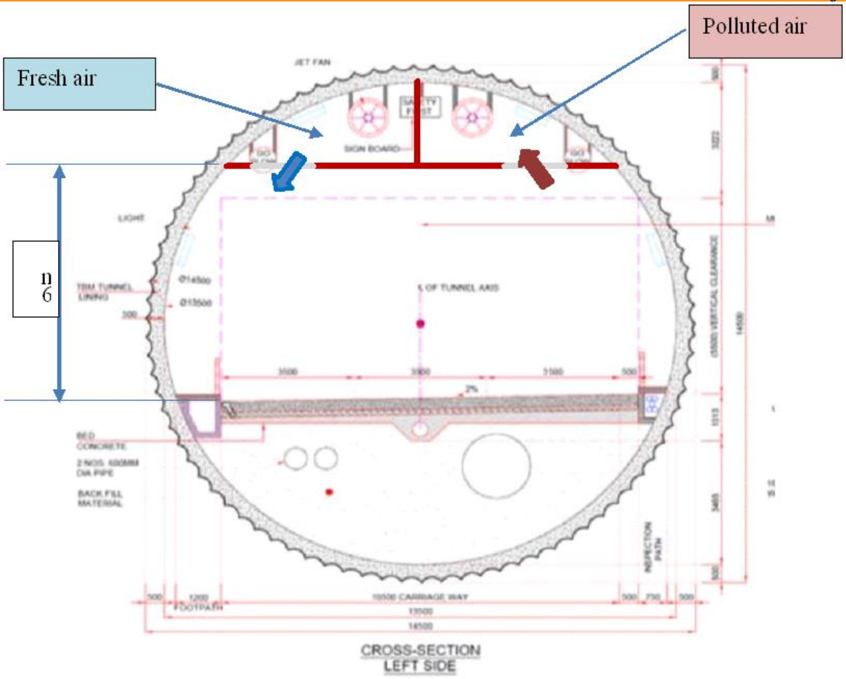

Figure 8: Schematic of the duct arrangement for the transverse system in the cross-section

Figure 9 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.

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. Table 14 gives the design values calculated for the current arrangement.

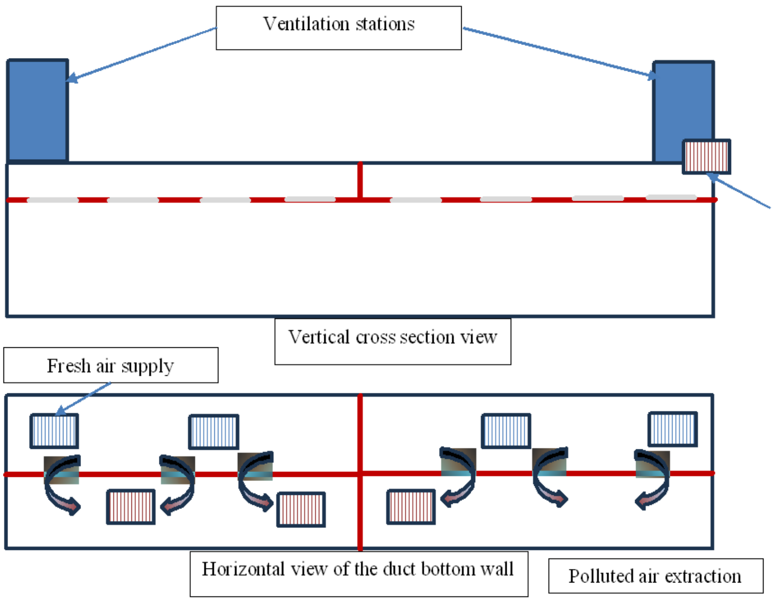

Figure 9: Schematic of the duct for transverse system (longitudinal views)

Table 14 : Design values for the transverse system 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, m	1,943.5	Two ventilation blocks
Fresh air rate, m^3/s	165.5× 2	For NOx; Two ventilation blocks
Pressure drop in duct, Pa	453	Per duct
Fan flow rate, m^3/h	90000	
Fan area (dia), m^2 (m)	0.79 (1)	
Pressure rise by fan, Pa	27	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)

1.9 Computational Analysis to Verify the Designed Ventilation System

Once the ventilation system is designed in terms of dimensioning and positioning of the system equipment's, it is proposed to verify the performance of the same for the typical traffic condition and pollution load using computational analysis. This will include the simulation and estimation of following parameters for a particular traffic condition

1) Vehicle emissions
2) Tunnel air flow
3) Fan flow
4) Ventilated air flow distribution and quality assessment

These parameters will be analysed for a particular section of interest to verify the designed ventilation system for its dimensioning and positioning of equipment. Computational analysis will be performed with very well validated commercial software.

1.10 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.

1.10.1 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. 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) with a duration of this fire is 30-60 minutes. Hence a heat release rate of 10 MW for a duration 60 minutes is chosen for the design. The range of smoke release rate is 20–300 m^3/s (Section 5.9.1, IRC-SP91-2019). Assuming a linear correlation between the heat and smoke release rates a smoke release rate of 30 m^3/s at the maximum gas temperature of 1350°C is taken.

1.10.2 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 90 minutes 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.

In the present case the traffic will be taken to be uni-directional and a "stop" condition in case of the kind of fire mentioned in the section on heat release rate.

1.10.3 Design and Dimensioning of Ventilation System

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). An example is shown in the following figure.
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 will be verified using 3D CFD calculations and suggest 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 30 m^3/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 recommended to use ducts and hence the transverse system of ventilation. The same transverse system designed for the pollutant dilution with a minimum added 10% air flow rate and 20% increase in power should be used.

1.11 Recommendation for the whole tunnel ventilation system

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 and given in Section 1.9.3.2. These values are for the ventilation system to dilute the pollutants. The maximum flowrate for the fans has to be increased by 10% and the power by 20% keeping the distance between them same. Total length of the tunnel system is about 50km. Based on this the total requirement of the fans recommended is given in Table 15.

Table 15 : Total fan requirement

Property	Value
Number of fans	900
Flow rate, m3/h	100000
Fan area (dia), m2 (m)	0.79 (1)
Pressure, Pa	32 (for the duct cross section area)
Power per fan, kW	30 (minimum)
Distance between fans, m	110 (with two fans at a section)

Total estimated power requirement for operating fans is 27000 kW.

The arrangement of the duct and the positions of the fans are shown in following drawings.

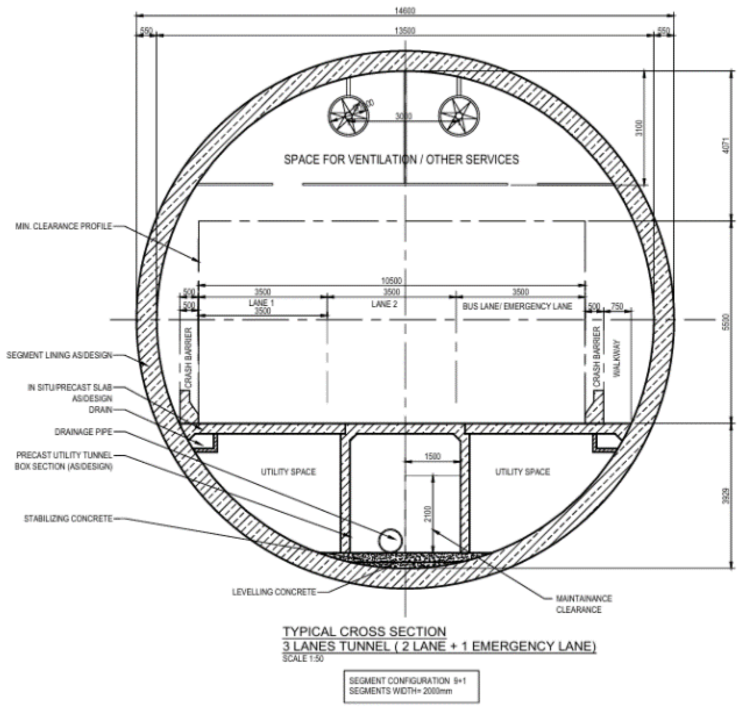

Figure 10: Typical cross section with duct and fans

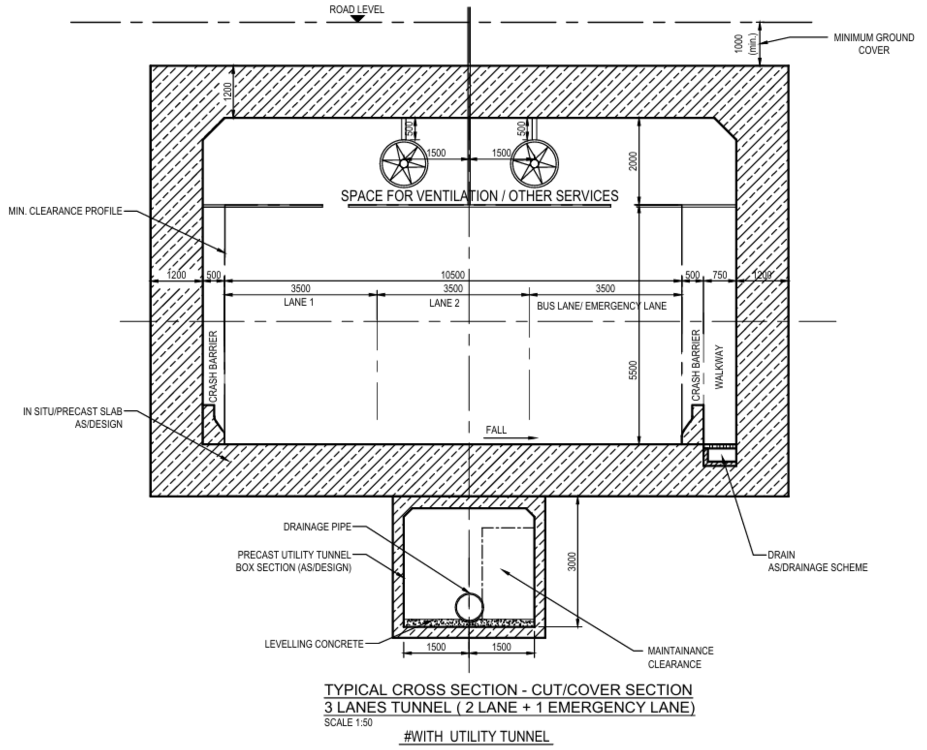

Figure 11: Cut and cover section

1.12 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 (if used)
- Closed Drainage System
- Fire Engines (if owned)

Following recommendations are given in IRC (2019), PIARC (1999) an NFPA 502:

- Fire detection systems available. These include detectors of heat (temperature and rate of rise), smoke, and flame. In addition, there are spot and linear heat detectors, the latter being preferable. 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.
- 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 of 90 meters
- 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. The standpipes can be either wet or dry. Hydrants should be placed at a spacing of 100 to 200 m. The between hose connections is recommended to 85 meters.

- The high pressure water mist pumps are connected to a tank. 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.
- For drainage system, two pipe systems are proposed to carry soil and waste separately. Waste pipes are connected to manhole through gully trap and soil pipes are to be directly connected to the manhole. Each fixture in the system shall be vented to the atmosphere to provide protection of trap seals against siphonage and gas leak due to positive pressure, to promote rapid and silent flow of waste, and to ventilate the sanitary system to reduce corrosion. Floor drain in guest room bathrooms should be avoided. If required, provide traps with trap primers to eliminate the potential for methane gas entering guestrooms. Air-gaps on sanitary system drains for food service equipment shall be provided. When sewer ejectors are required, duplex submersible sump pump system with each pump sized at 65% of peak load shall be provided. System includes control panel for alternating pumps.
- 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. Sprinkler arrangement is recommended to be used at every 100 m

1.13 References

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