LONGITUDINAL VENTILATION SYSTEM FOR A LONG ROAD-TUNNEL: OPTIMAL DESIGN WITH BATTERIES OF JET FANS AND CHALLENGES TO OVERCOME EXTREME FOGGY WEATHER CONDITION

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ABSTRACT

An optimal design solution for a long road-tunnel mechanical ventilation system with an application of batteries of jet fans at a location where extreme foggy weather conditions prevails for a third of the year. The main purpose is to make it practically feasible, by applying the concept of longitudinal ventilation system, as well as optimizing the design to keep the vehicular pollutants under control and fully functional to high standard of international design parameters and criterion, even during heavy fog and rainfall, for normal mode ventilation, particularly during congestion and slow-moving traffic, as well as to cater to an effective smoke management at any probable locations of the fire scenarios.

The design will be innovative for application for such a long road-tunnel with heavy traffic profile, and very practical for application that will harmonize with good engineering practices and international codes and guidelines with an objective to achieve highest standards of safety criteria, both during normal and emergency situations.

Keywords: Design, Foggy, Longitudinal, Road-Tunnel, Ventilation, Extinction Coefficient Fire, Smoke.

1. INTRODUCTION

The purpose of this paper is to identify and address the challenges faced to overcome the extreme foggy weather condition that prevails during rainy climatic conditions for a third of the year in the location of this long road tunnel at a medium altitude hilly terrain.

The longitudinal mechanical ventilation system design philosophy with batteries of jet fans being adopted for this 8.67 km long unidirectional rural parallel twin tube road tunnel with four traffic lanes in each tunnel-bore, because of the terrain and inaccessibility for an intermediate ventilation shaft(s), as well as for the protection of the wildlife and the forest, specifically in the region where these twin tunnels are passing through.

The main purpose is to make it practically feasible, as well as optimizing the design to keep the vehicular pollutants under control and fully functional to high standard of international design parameters and criterion, even during heavy fog and rainfall, for normal mode ventilation, particularly during congestion and slow-moving traffic, as well as to cater to an effective smoke management at any probable locations of the fire incident.

The detailed design of the ventilation system has been independently carried out with both PIARC [1] and RVS [2] guidelines for the vehicle emission and fresh air demand for ventilation calculations. However, in this paper the design with PIARC the methodology, design aspects and details with calculations are discussed here in this paper.

2. DESIGN

2.1 Design parameters under consideration for this case study

2.1.1 Physical design parameters and geometry of unidirectional rural parallel twin tunnels.

Table 1: Physical Parameters and Geometry of the Tunnels

Parameters	Dimensions
Length of the Tunnels:	8.67 Km
Number of Tunnel Bore:	2 tunnels
Number of Lanes per Tunnel:	4 lanes
Maximum Tunnel Altitude above sea level (@ East Portal):	700 m
Tunnel Slope / Gradient:	± 2.0 %
Tunnel Cross-sectional Area:	202 sqm
Tunnel Perimeter:	60 m
Maximum Height at the Tunnel Crown:	9.5 m
Tunnel Width at the Pavement Level:	23.5 m

2.1.2 Traffic Input Data

Table 2: Traffic Profile and Density and Designed Vehicle Speed

Parameters	Dimensions
Annual Average Daily Traffic (AADT)	65,000 vehicles/day
Peak Hour Traffic Volume @ 10% of AADT	6,500 vehicles/day
Therefore, Peak Hour Traffic Volume per Tunnel	3,250 vehicles/hour/tunnel
Henceforth, Peak Hour Traffic Volume per Lane	813 vehicles/hour/lane
Maximum Design Speed of the Vehicles	130 Km/hour

Table-3: Traffic Composition

Category:	Passenger Cars (PC)		Light Commercial Vehicles (LCV)			Heavy Goods Vehicles (HGV)				
Type:	Car	Taxi	LMV	LCV	Mini Bus	Std. Bus	2 Axle	3 Axle	MAV (4-6 Axle)	MAV (>6 Axle)
Percentage:	39%	15%	5%	10%	2%	5%	5%	4%	10%	5%
Fuel Type Composition:										
Gasoline:	23%		1%			-				
Diesel:	31%		16%			29%				

2.1.3 Traffic Output Profile: Calculated [1] for the Peak Hour Traffic with the Data of Table-1, 2 & 3 above

Table 4: Fleet Composition in Both Tunnel at Different Traffic Vehicular Speed [for Down-Hill / Up-Hill Tubes]

Vehicle Speed (Km/hour)	No. of Vehicles in Tunnels	No. of Cars		No. of LCV		No. of HGV		
		Gasoline	Diesel	Gasoline	Diesel	15t	23t	32t
0	3292	764	1013	22	537	165	296	494
10	1536	357	473	10	251	77	138	230
20	1409	327	434	10	230	70	127	211
30	939	218	289	6	153	47	85	141
40	704	164	217	5	115	35	63	106
50	564	131	173	4	92	28	51	85
60	470	109	145	3	77	23	42	70
70	403	93	124	3	66	20	36	60

80	352	82	108	2	57	18	32	53
90	313	73	96	2	51	16	28	47
100	282	65	87	2	46	14	25	42
110	256	59	79	2	42	13	23	38
120	235	55	72	2	38	12	21	35
130	217	50	67	1	35	11	20	33

2.1.4 Basis of Emission criteria being considered for estimation of the vehicular emission and pollution dilution by standard approach [1].

Table-5: Design Emission Criteria

Description	Data
Base Year for the Emission Rates:	2018
Technology Standard Group / Class:	C
Design Year:	2030
Corresponding Time Shift Applicable:	10 years
Therefore, Year of Base Emission Rates for Class C:	2020

Table 6: Design Threshold Values for Emissions

Pollutants	Design Parameters	Equivalent in g/m^3
Carbon Monoxide, CO (ambient)	5 ppm	5.716 mg/m^3
Carbon Monoxide, CO (admissible)	70 ppm	80.031 mg/m^3
Nitrogen Dioxide, NO2 (ambient)	0.1 ppm	0.188 mg/m^3
Nitrogen Dioxide, NO2 (admissible)	1 ppm	1.878 mg/m^3
Percentage of NO2 in NOx	20%	
Extinction Coefficient (Admissible), K (admissible)	0.005 m^{-1}	
Extinction Coefficient (Ambient), K (ambient)	0.000 m^{-1}	

2.2 Fresh Air Flow Rate Demand and Visibility Condition During Dense Foggy Weather

2.2.1 Determination of fresh air demand for standard operation

Fresh Air Flow Rate Demand Calculated [1] for the Peak Hour Traffic at every 10 km/hour intervals from standstill traffic (0 Km/hour) to maximum design vehicular speed of 130 km/hour, for both down-hill and up-hill tunnels by adopting standard approach for the emission estimation [1] along with the Data of Table-4, 5 & 6 above.

Table 7 & 8: Fresh Air Flow Rate Demand for Down-Hill Tunnel & Up-Hill Tunnel

Vehicle Speed (Km/hour)	Table-7: Down-Hill Tunnel						Table-8: Up-Hill Tunnel				
	CO (m^3/s)	NO2 (m^3/s)	Opacity (m^3/s)		Max Air Demand (m^3/s)		CO (m^3/s)	NO2 (m^3/s)	Opacity (m^3/s)		Max Air Demand (m^3/s)
0	29	538	130		538		29	538	130		538
10	44	1077	257		1077		59	1342	311		1342
20	45	1006	295		1006		72	1378	359		1378
30	29	680	236		680		48	1003	302		1003
40	23	486	210		486		44	871	285		871
50	20	371	193		371		39	767	271		767
60	16	312	182		312		38	869	268		869
70	16	273	177		273		41	950	273		950
80	15	250	177		250		43	1053	280		1053

90	14	250	174		250		44	1033	284		1033
100	15	248	177		248		45	1021	282		1021
110	17	282	179		282		56	1051	282		1051
120	21	327	184		327		75	1080	283		1080
130	32	388	190		388		117	1142	290		1142
Max FA Demand	@ Down-Hill Tunnel			**1077** m^3/s @ 10 Km/h due to NO2			@ Up-Hill Tunnel:			**1378** m^3/s @ 20 Km/h due to NO2	

2.2.2 Fresh air demand with respect to foggy weather situations

Also, to evaluate the visibility situations due to extreme foggy weather conditions during monsoon season, fresh air flow rate demand has been calculated for the same peak hour traffic at various vehicular speeds as in sl. no. 2.2.1 above, with enhanced visibility extinction coefficient values – ranging from design value of 0.005 m^{-1} up to 0.001 m^{-1}. The detailed effects on the fresh air demand at various extinction coefficient values has been summarized in Table-9 below. It has been observed that the maximum fresh air demand requirement in both the down-hill and up-hill tunnels has little or no changes up to extinction coefficient value of 0.002 m^{-1}. However, at extinction coefficient value of 0.001 m^{-1} there is a significant change in the maximum fresh air demand requirement in both the down-hill tunnel (increases by 37%) and up-hill tunnel (increases by 30%) than that of with the design extinction coefficient value of 0.005 m^{-1}. The effects due to this aspect has been analyzed, for various factors having potential toward affecting visibility inside the tunnel, with detailed study on the optimal design length of light beam, in the subsequent clauses 2.2.3 to 2.2.6, below.

Table 9: Fresh Air Flow Rate Demand Summary for Multiple Extinction Coefficients to Evaluate the Visibility Situations due to Extreme Foggy Weather during Monsoon for Normal Mode Ventilation

Fresh Air Demand with Design Extinction Coefficient:			**0.005 m^{-1}**		**0.003 m^{-1}**		**0.002 m^{-1}**		**0.001 m^{-1}**	
Vehicle Speed (Km/hour)	*CO (m^3/s)	*NO$_2$ (m^3/s)	Opacity (m^3/s)	Max Air Demand (m^3/s)	Opacity (m^3/s)	Max Air Demand (m^3/s)	Opacity (m^3/s)	Max Air Demand (m^3/s)	Opacity (m^3/s)	Max Air Demand (m^3/s)
Down-Hill (LHS) Tunnel										
0	29	538	130	538	217	538	325	538	651	651
10	44	1077	257	1077	428	1077	642	1077	1283	1283
20	45	1006	295	1006	492	1006	738	1006	1477	1477
30	29	680	236	680	394	680	591	680	1182	1182
40	23	486	210	486	349	486	524	524	1048	1048
50	20	371	193	371	322	371	483	483	966	966
60	16	312	182	312	303	312	454	454	908	908
70	16	273	177	273	296	296	444	444	887	887
80	15	250	177	250	295	295	442	442	884	884
90	140	250	174	250	290	290	435	435	871	871
100	15	248	177	248	294	294	442	442	883	883
110	17	282	179	282	298	298	446	446	893	893
120	21	327	184	327	307	327	461	461	921	921
130	32	388	190	388	316	388	474	474	949	949
Max Fresh Air Demand @ Down-Hill Tunnel:			**1077** m^3/s @ 10 Km/h due to NO$_2$		**1077** m^3/s @ 10 Km/h due to NO$_2$		**1077** m^3/s @ 10 Km/h due to NO$_2$		**1477** m^3/s @ 20 Km/h due to Opacity	
Up-Hill (RHS) Tunnel										
0	29	538	130	538	217	538	325	538	651	651
10	59	1342	311	1342	518	1342	777	1342	1553	1553
20	72	1378	359	1378	598	1378	896	1378	1793	1793
30	48	1003	302	1003	503	1003	755	1003	1509	1509
40	44	871	285	871	476	871	714	871	1427	1427
50	39	767	271	767	452	767	678	767	1356	1356
60	38	869	268	869	447	869	671	869	1341	1341

70	41	950	273	950	454	950	681	950	1363	1363
80	43	1053	280	1053	467	1053	701	1053	1402	1402
90	44	1033	284	1033	474	1033	711	1033	1421	1421
100	45	1021	282	1021	470	1021	705	1021	1411	1411
110	56	1051	282	1051	470	1051	704	1051	1409	1409
120	75	1080	283	1080	472	1080	707	1080	1415	1415
130	117	1142	290	1142	483	1142	725	1142	1450	1450
Max Fresh Air Demand @ Up-Hill Tunnel:			**1378** m^3/s @ 20 Km/h due to NO_2		**1378** m^3/s @ 20 Km/h due to NO_2		**1378** m^3/s @ 20 Km/h due to NO_2		**1793** m^3/s @ 20 Km/h due to Opacity	
Note: * Fresh Air demand remains unaffected for CO & NO_2 with various Design Extinction Coefficients.										

2.2.3 Determination of Extinction Coefficient

Comparative study of the extinction coefficient with respect to percentage of intensity of the light at the receiver vis-s-vis intensity of the light source, according to extinction coefficient expressed by equation (1), below.

$$K = -\frac{1}{L} . ln\left\{\frac{I}{Io}\right\} \qquad (1)$$

L = Beam length between source and receiver, *Io* = Intensity of the Light Source, *I* = Intensity of the Light at the Receiver

2.2.4 Dense Fog Analysis

- The mass concentration of $PM_{2.5}$ ($\mu_{PM2.5}$) is ranged from 121–375 $\mu g/m^3$, and the interaction between fog droplets and fine particles is analyzed [3].
- And with the equation 5 [1]: Extinction Coefficient, $K = f_{vis}.\mu_{PM2.5}$
  Where, f_{vis} is a conversion factor = 0.0047 m^2/mg
  $\mu_{PM2.5}$ = 375 $\mu g/m^3$ + 15% (in excess for more safety) = 430 $\mu g/m^3$
- Therefore, due to dense fog in the atmosphere the Extinction Coefficient at ambient is, K_{amb} = 0.002 m^{-1}

Table 10: Comparative of Visibility Condition & Fog Analysis Visibility Condition vis-à-vis Extinction Coefficient

Parameters	Design Criteria	Comparisons of Visibility Condition						Fog Analysis Visibility Condition		
Extinction Coefficient (Admissible), K_{adm} (m^{-1})	**0.005**	0.003		0.002		0.001		**0.005**		**0.007**
Extinction Coefficient (Ambient), K_{amb} (m^{-1})	**0**	0		0		0		**0.002**		**0.002**
Extinction Coefficient (Difference), $K = K_{adm} - K_{amb}$ (m^{-1})	**0.005**	0.003		0.002		0.001		**0.003**		**0.005**
Percentage of Intensity of the Light at the Receiver (I) w.r.t. Source (Io), I/Io (%)	**20%**	20%	38%	20%	52%	20%	72%	20%	38%	20%
Length of Light Beam, L (m)	**322**	536	322	805	322	1209	322	536	322	322
Remarks / Observations	More Light beam length @ design I/Io ratio &Better I/Io ratio @ design Light beam length									

2.2.5 Impact on Fresh air demand vis-à-vis extinction coefficient

The comparative study of Table-10 vis-à-vis Table-9 above reflects that by enhancing the extinction coefficient, resulting considerable enhancement of either the length of light beam or the percentage of intensity of the light at the receiver, the fresh air demand has very little or no changes up to an extinction coefficient value of 0.002 m^{-1}. Therefore, preliminary review and study could be conclusive that during extreme foggy weather conditions in the region the estimated fresh air demand can meet the visibility parameters comfortably up to an extinction coefficient value of 0.002 m^{-1} (i.e., having at least 805 m long light beam with 20% intensity [1] of the light at the receiver or safe design light beam length of 322 m with 52% intensity of the light at the receiver) without any modification in the normal ventilation design criteria adopted, even though quantum of fresh air requirement increases for pollution dilution due to opacity, by considering enhancing admissible extinction coefficient and zero ambient extinction coefficient. But, the fresh air requirement for dilution of NO_2 still governs here in the design criteria of this particular case study, except for certain higher vehicular speed at enhanced extinction coefficient in the down-hill tunnel where fresh air demand is governed due to opacity dilutions. Nevertheless, these have an insignificant impact in the design as the ventilation system been designed for maximum fresh air demand requirement at congested slow traffic movement.

Furthermore, the results of the extinction coefficients with dense fog analysis in Table-10 above indicates that with K = 0.003 m^{-1} or 0.005 m^{-1} it shall still be within the acceptable limit of visibility (i.e., having at least 536 m long light beam with 20% intensity of the light at the receiver or safe design light beam length of 322 m with 38% intensity of the light at the receiver or at least 322 m long light beam with 20% intensity of the light at the receiver even when considering in the design with hazy extinction coefficient of 0.007 m^{-1} prevailing inside the tunnel) without any modification in the normal ventilation design criteria adopted, even though quantum of fresh air requirement increases with decreasing differences of extinction coefficient between admissible and ambient for pollution dilution due to opacity, but the fresh air requirement for dilution of NO_2 still governs here in the design criteria of this particular case study.

2.2.6 Visibility Analysis for a Safe Stopping Sight Distance

Safe Stopping Sight Distance (SSSD) is the distance required for a driver to bring the vehicle to a stop after observing any object on the road. It is calculated based on the design speed of the road and the reaction time of the driver. Following formulas [4] are adopted to calculate the SSSD:

$$SSSD = LD + BD$$

LD = Lag or Reaction Distance = $V.tR$
BD = Braking Distance = $V^2.\left[\frac{1}{2.g.f+s}\right]$
V = Design Vehicle Speed in metre per second
tR = Reaction Time in seconds
g = Acceleration due to Gravity = 9.81 metre/second^2
f = Coefficient of Longitudinal Friction = 0.35 ~ 0.40 [5]
s = gradient in %

Table 11: Effects of Visibility Condition due to Safe Stopping Sight Distance (SSSD)

Design Vehicle Speed, V (Km/h)	10	20	30	40	50	60	70	80	90	100	110	120	130
Safe Stopping Sight Distance, SSSD (m)	8	19	32	47	65	85	107	132	159	189	221	255	292
Light Level (i.e., I/Io in %) @ Extinction Coefficient, K = 0.005 m^{-1}	96%	91%	85%	79%	72%	66%	59%	52%	45%	39%	33%	28%	23%

Note: Therefore, Table-11 vis-à-vis Table-10 above concludes that since the Length of Light Beam, L = 322 m [@ Minimum Acceptable Visibility or Light Level (i.e., I/Io = 20%) and Design Extinction Coefficient, K = 0.005 m^{-1}] is Greater than SSSD as well as I/Io Ratio at all Design Speed, the adopted Design Basis is safe and holds good.

2.3 Jet Fan Calculation Procedure for Longitudinal Ventilation

2.3.1 Total Pressure and Thrust in the Tunnel

To determine the quantities / number of jet fans required for the longitudinal road tunnel ventilation system it is pertinent to determine the total thrust required to overcome the gross total pressure drops / losses in the tunnel [6].

The total pressure loss and thrust in the tunnel defined by the following equations:

$$\Delta P_{Total} = \Delta P_{ent} + \Delta P_{exit} + \Delta P_{wf} + \Delta P_{w} + \Delta P_{veh} + \Delta P_{ce} + \Delta P_{fire} + \Delta P_{met} \quad \text{.........} (1)$$

$$T_{Total} = \Delta P_{Total} \times A_{Tunnel} \quad \text{.........} (2)$$

ΔP_{Total} = total pressure drops (in **Pa**)
T_{Total} = total thrust required (in **N**)
A_{Tunnel} = tunnel cross-sectional area (in **m^2**)
ΔP_{ent} & ΔP_{exit} = pressure drops due to tunnel entrance and exit
ΔP_{wf} = pressure drops due to tunnel wall friction
ΔP_{w} = pressure drops due to adverse wind
ΔP_{veh} = pressure drops / gains due to vehicles / piston effects
ΔP_{ce} = pressure drops due to chimney effect / fire buoyancy
ΔP_{fire} = pressure drops due to fire blockage (in fire scenario only)
ΔP_{met} = pressure drops due to meteorological conditions

2.3.2 Jet Fan Estimation

Number of operating jet fans required for the longitudinal road tunnel ventilation system [6] is calculated by the following equations:

$$N_{Jet\ Fan} = \{T_{Total}\} \div \{T_{Jet\ Fan} \times (\eta_i \times \eta_v \times \eta_\rho)\} \quad \text{....} (3)$$

$N_{Jet\ Fan}$ = number of operating jet fans
T_{Total} = total thrust required (in **N**)
$T_{Jet\ Fan}$ = nominal jet fan thrust (in **N**)
η_i = installation efficiency
η_v = velocity derating factor
η_ρ = density derating factor

2.3.3 Longitudinal Tunnel Ventilation Summary

With the above equations in clauses 2.3.1 & 2.3.2 the results [6] are summarised and tabulated below in Table-12 for the fresh air flow rate demand and visibility condition during dense Foggy weather, as designed at clause 2.2 above, for normal mode tunnel ventilation, as well as for the fire mode ventilation.

Table 12: Battery of Jet Fans for Longitudinal Tunnel Ventilation

Ventilation Parameters	Normal Mode		Emergency (Fire) Mode	
	Down-Hill Tunnel	Up-Hill Tunnel	Down-Hill Tunnel	Up-Hill Tunnel
Maximum Fresh Air Demand (m/s^3) @ Dense Foggy Weather with 0.002 m^{-1} Ext. Coeff.	1077	1378	-	-
Critical Velocity @ Fire size of 200 MW (m/s)	-	-	3.30	3.55
Total Thrust Required (N)	141058	198507	131230	133287
Selected Jet Fan Thrust (N)	2200	2200	2200	2200
Installation Efficiency, η_i =	0.8	0.8	0.8	0.8
Velocity Derating Factor, η_v =	0.83	0.79	0.90	0.89
Density Derating Factor, η_ρ =	0.87	0.87	0.79	0.82
Total Number of Operating Jet Fans	111	165	105	104
Number of Jet Fans mounted in each location	3	3	3	3
Max equal distance between Jet Fans sets (m)	228	155	241	243
Min recommended distance between Jet Fans sets [7] is 10 x tunnel hydraulic diameter (m)	135	135	135	135

2.3.4 Smoke Management Consideration

In the above Table-12 vis-à-vis explanations given in the above clauses 2.2.2, 2.2.5 & note @ 2.2.6, along-with 1-D Simulation [6] with a Fire size of 200 MW HRR, the number of Jet Fans batteries, required for a design criteria and dense foggy condition for a normal mode longitudinal ventilation system, shall be sufficient for an effective smoke management at the worst probable locations of the fire scenarios. Furthermore, the recommended distance between jet fan sets [7][8] and the economics of the optimization on the design for the installation of these jet fans near the portals [9] are also adhered to.

3. SUMMARY AND CONCLUSION

The above analysis and study with detailed calculations of the longitudinal mechanical ventilation system designed, with batteries of jet fans mounted at the crown of the tunnels, for normal mode operation reflects that even during extreme foggy weather condition the basic acceptable limit of visibility will be achievable without any modification to the system for the selected normal mode ventilation basic design criterion.

Even though the quantum of fresh air requirement increases with decreasing differences of extinction coefficient between admissible and ambient for pollution dilution due to opacity, the fresh air requirement for dilution of NO_2 still governs here in the design because of a very high standard of international design criterion being adopted for nitrogen dioxide.

Furthermore, the longitudinal mechanical ventilation system for normal mode shall also cater to an effective smoke management, up to a fire size of 200 MW HRR, at any probable locations of the fire scenarios, with the selected jet fans specifications and quantities.

It can be concluded that the adopted design is optimized with a very reliable functional requirement achievability for all weather conditions and stringent safety standards.

4. REFERENCES

[1] PIARC 2019R02EN – Road Tunnels: Vehicle Emissions and Air Demand for Ventilation

[2] RVS 09.02.32 June 2010 – Tunnel Equipment Ventilation Systems Fresh Air Demand: Air Demand Calculation

[3] Paper: "*Fog Droplet Size Distribution and the Interaction between Fog Droplets and Fine Particles during Dense Fog in Tianjin, China*" – by Qing Liu, Bingui Wu, Zhaoyu Wang and Tianyi Hao [Read full-text or Download full-text PDF at: https://www.researchgate.net/publication/339761583_Fog_Droplet_Size_Distribution_and_the_Interaction_between_Fog_Droplets_and_Fine_Particles_during_Dense_Fog_in_Tianjin_China]

[4] Paper: "*Sight Distances: Lecture Notes in Transportation Systems Engineering*" – by Prof Tom V. Mathew [https://www.civil.iitb.ac.in/tvm/nptel/303_SigDst/web/web.html]

[5] Highway Engineering Design Data Hand Book (Geometric Design & Pavement Design) Compiled by Dr. P. Nanjundaswamy / IRC

[6] Detailed calculation procedures, 1-D simulation and results are incorporated under a separate design head / volume of this paper. Not able to submit as a part of this paper because it is quite extensive and voluminous to restrict within the stipulation of not exceeding 8 pages. However, if permitted, I can include the same in this paper or submit separately.

[7] PIARC 05.02.B – 1995: Vehicles Emissions Air Demand Environment Longitudinal Ventilation: *Article IV.2.1 (c) @ page-51 – Longitudinal distance* (η_3)

[8] 2011 ASHRAE Handbook – HVAC Applications: Chapter-15: Enclosed Vehicular Facilities: Equipment – Fans – Number & Sizes of Fans @ 15.33

[9] PIARC 05.05.B – 1999: Fire and Smoke Control in Road Tunnels: *Article V.1.2.1; last para @ page-145 – Longitudinal system*