I-70 East Project, Denver, CO Partial Covered Lowered Alternative

Ventilation and Fire Life Safety Report

Atkins North America

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Glossary and definitions

Term	Definition
AADT	Annual Average Daily Traffic
AHJ	Authority Having Jurisdiction
BLEVE	Acronym for Boiling Liquid Expanding Vapour Explosion. The BLEVE is an explosion due to flashing of liquids when a vessel containing a high vapour pressure substance fails.
CDOT	Colorado Department of Transportation
DARTS	Durable and Reliable Tunnel Structures (research project)
FEMA	Federal Emergency Management Agency (US government)
FFFS	Fixed Fire Fighting System
FHWA	Federal Highway Administration (US)
Flash Fire	A flash fire is the non-explosive combustion of a vapour cloud resulting from a release of flammable material into the open and which after mixing with air, ignites in the presences of an ignition source.
GP	General Purpose (with reference to traffic lanes)
HGV	Heavy goods vehicles (Trucks)
I70	Interstate 70
Jet Fire	A jet fire occurs when flammable gas releases from the pipeline (or hole) and the released gas ignites immediately. Damage distance depends on the operating pressure and the diameter of the hole or opening flow rate.
ML	Managed lanes (toll lanes)
MOVES	Motor Vehicle Emission Simulator
PCU	Passenger Car Unit
PIARC	Permanent International Association of Roads Congress (World Road Association)
US EPA	United States Environmental Protection Agency
WHO	World Health Organization

Executive summary

The location of the covered section is taken to be between Clayton Street and Columbine Street and estimated to be 304m (less than 1,000 ft.) in length with a cross section that varies in width. In each covered section, west bound and east bound comprising three General Purpose (GP) lanes, two managed toll lanes and one on/off ramp, making a total of 6 traffic lanes. In addition to the traffic lanes there are two hard shoulders outside the GP / Toll lanes and a striping separating the GP from toll lanes.

The ventilation, fire and life safety requirements have been developed in line with NFPA 502, 2014 Edition and supporting international good practice based upon the following key safety objectives:

- Permit the users of the covered section of the I70 East highway study area to evacuate in reasonable safety;
- Reduce the life safety risk to as low as reasonably practicable;
- Allow fire department personnel to operate in reasonable safety

Based on the NFPA standard, the covered section of the I70 is classified as a Category C tunnel by virtue of the high traffic peak volumes and the covered section length. The mandatory requirements for the cover are: means of identifying fire location, fire alarm control panels, communication systems, fire protection systems (excluding fire pumps, emergency ventilation, which are conditionally mandatory; and fire apparatus which is non-mandatory). Means of egress and electrical systems are also mandatory for a Category C tunnel.

NFPA 502 (2014) has introduced new requirements and also modified some of its previous requirements for a Category C tunnel. Amongst the new mandatory requirements for a Category C tunnel are engineering analysis and protection of structural elements. The new conditionally mandatory elements are: emergency communications systems (previously mandatory), fixed fire suppression, flammable and combustible environmental hazards analysis.

Given the NFPA requirements, the I70 covered section is to be provided with commensurate fire safety provisions including consideration of a fixed fire fighting system (FFFS) and mechanical ventilation.

In this report, FFFS is recommended for the I-70 Cover to limit fire growth to a peak of 60MW; and to further limit the residual convective heat release rate seen by the ventilation system to 30MW. In addition to controlling fire growth and limiting the size of fire that needs to be controlled by the ventilation system, FFFS offers further benefits associated with the support of fire fighting, protection of the structure and equipment and enabling the more rapid re-opening of the tunnel; limiting associated traffic delays and maximising availability. Design and development of specifications is to proceed on this basis pending approval of the AHJ.

FFFS and ventilation concepts are presented in this report. The FFFS concept comprises a water based system (foam additives could be used) which operates on a zonal basis (it is estimated that the I70 cover would have 12 zones). The operating principle is that upon confirmation of fire emergency, three zones of approximately 25m per zone are activated simultaneously to control the fire until the fire department take control of the fire situation. Details of design such as system type, flow rates and operational pressures will be subject to further development.

Assessment has been made of the need for a mechanical ventilation system considering two main aspects: to control air quality and the control of heat and smoke in the case of fire. Air quality control requirements have been assessed using the Motor Vehicle Emission Simulator (MOVES). The results show that with stationary traffic in the covered section and no significant natural portal pressure difference, the exposure limit for NO_2 would be reached first, taking about 30 minutes. This relatively short time indicates that a ventilation system is advisable and is therefore recommended in order to control pollution levels within the covered section.

The ventilation system is sized for smoke control; as the ventilation capacity required for smoke control is significantly greater than that for pollution. Ventilation is to be designed to work in harmony with the FFFS. The proposed concept for the ventilation of the tunnel is a mechanical longitudinal ventilation system consisting of a single row of evenly-spaced jet fans of 1.12m diameter located in a structural niche at the entrance of each portal; specifically 13 jet fans in the westbound and 12 jet fans in the eastbound.

1. Scope

1.1. Objectives

ANA has been commissioned by the Colorado Department of Transportation (CDOT) for the development of the I70 East Project, Denver, Colorado. Atkins Ltd (AUK) in the UK were commissioned by ANA to prepare a Ventilation and Fire Life Safety Report looking into the principal Standards and Guidance documents that would be applicable and to develop recommendations for adoption within the scheme.

1.2. Limitations

The findings and recommendations contained within the Report are based upon standards and guidance documents currently available as at March 2015.

The findings and recommendations contained within this study report are subject to Acceptance, Approval and Adoption by CDOT and the AHJ.

1.3. Issue Version

Version 3.0 is issued in draft for client review updated to reflect new standard edition (in particular NFPA 502 2014 edition) and new available information to meet ANA/CDOT requirements.

1.4. Report Structure

The report is structured as follows:

- Section 2 of this report covers the location and geometry of the covered section of the I-70 East Highway, Denver;
- Section 3 presents information on air quality standards and pollution concentration limits coupled with the output from traffic emission modelling using the US EPA computer model MOVES;
- Section 4 provides detailed information on the ventilation, fire and life safety requirements for the covered and section of the highway;
- Section 5 summarizes the approach taken towards the design fire for ventilation and life safety purposes; including results of assessment of the ventilation system design fire maximum heat release rate based upon the likely return period of fires of different severities;
- Section 6 provides high level information on fixed fire fighting system design concept for the covered section;
- Section 7 provides details of a conceptual ventilation system design solution for the covered section.

2. Basis of design

2.1. Location, Geometry and Configuration

The location of the covered section of highway has been taken to be between Clayton Street and Columbine Street and estimated to be 304m (less than 1,000 ft.) in length as indicated in Figure 2-1. The wide cross section varies along the covered section from 80m (~262 ft.) on the east end to 60m (~197 ft.) on the west end with a constant downwards gradient of 0.89% for the first 40m (131 feet) from east to west and 1.2% for the rest of the covered area length (264m ~868 ft.). In each covered section, west bound and east bound comprising three General Purpose (GP) lanes, two managed toll lanes[1] and one on/off ramp, making a total of 6 traffic lanes. In addition to the traffic lanes there are two hard shoulders outside the GP / Toll lanes and a strip separating the GP from toll lanes as shown in Figure 2-2.

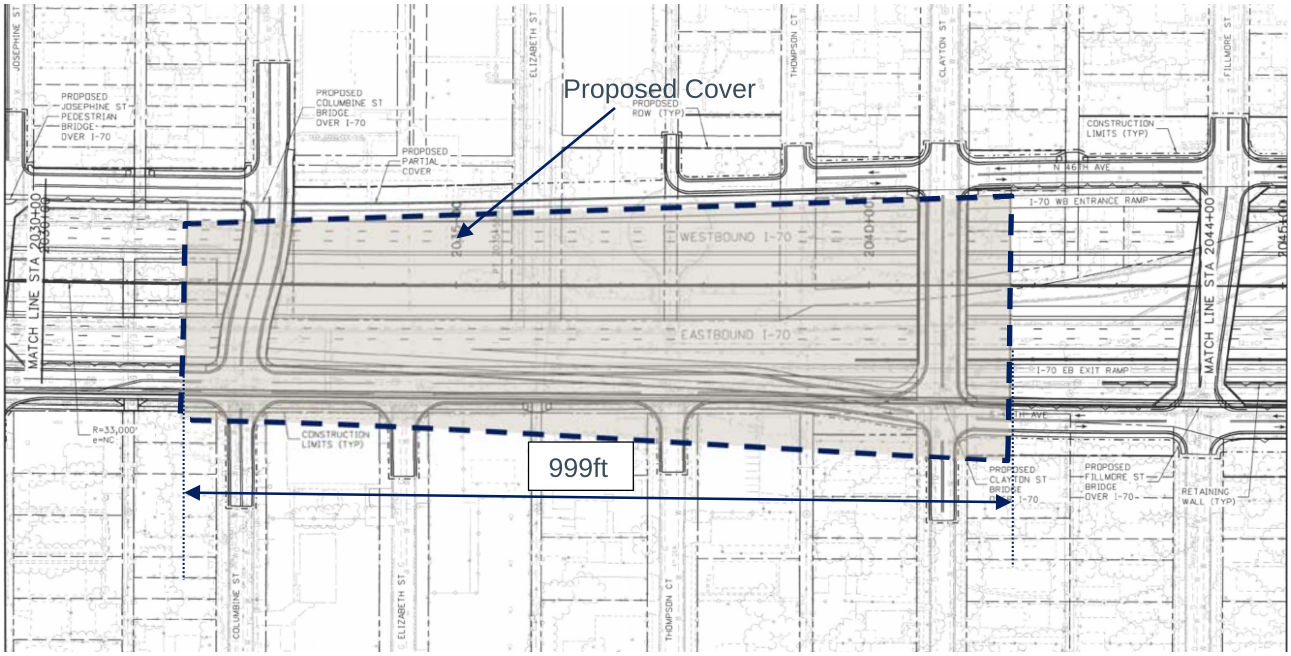


Figure 2-1 Plan view of proposed covered highway location [6]

[1] Current understanding is that the cover section will operate with 5 lanes when opened for the first time (around 2020's), the scheme is to add one additional managed lane by halving the hard shoulder (currently proposed 24' in the center wall, see Figure 2-2) at a later phase after opening (estimated year 2035).

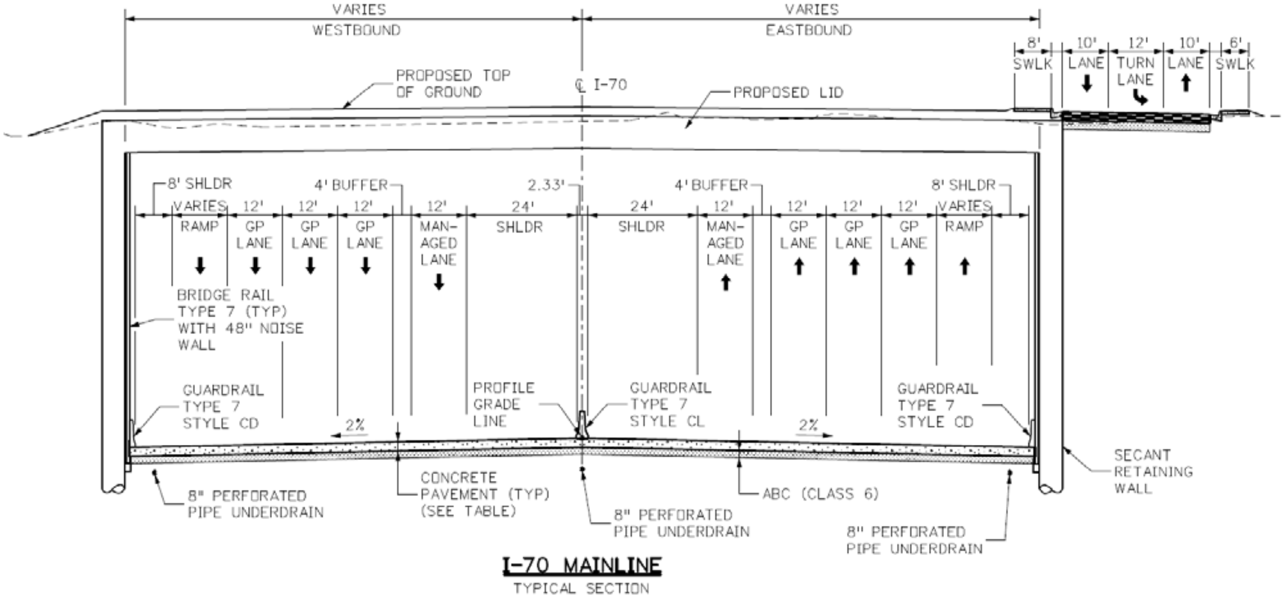


Figure 2-2 Typical section of covered area [7]

2.2. Vehicle Traffic

2.2.1. Traffic Mix

Vehicle traffic mix used for this study is based upon traffic data provided for the portal emissions analysis. There are 13 types of vehicles and these have been combined in order to provide simplified inputs for the fire frequency analysis (see Appendix B). Table 2-1 below shows the vehicle classification (as per [31]) and simplification:

Table 2-1 I-70 Vehicle mix

Provided vehicle mix data			Combined vehicle mix[2]	
linkID	**sourceTypeID**	**Fraction**	**Vehicle type**	**Percentage**
motorcycle	11	0.034	Cars & Vans	94.4%
pax car	21	0.487	buses	2.3%
pax truck	31	0.319	Heavy goods vehicles (trucks)	3.3%
light commercial truck	32	0.103		
intercity bus	41	0.004		
transit bus	42	0.003		

[2] Traffic mix combined for the purposes of Fire life Safety analysis

Provided vehicle mix data			**Combined vehicle mix[2]**	
linkID	**sourceTypeID**	**Fraction**	**Vehicle type**	**Percentage**
School bus	43	0.017		
Refuse truck	51	0.000		
single unit short haul truck	52	0.016		
single unit Long haul truck	53	0.001		
Motor home	54	0.002		
combination short haul truck	61	0.008		
combination long haul truck	62	0.006		
single unit Long haul truck	53	0.001		
	TOTAL	1		100%

Information by CDOT provided to ANA [31]

2.2.2. Traffic operating mode

Traffic is proposed to be unidirectional. Contraflow (bi-directional traffic in a single bore) has been assumed to be not required in the I70 tunnel.

3. Air Quality Requirements

3.1. Requirements

Project specific air quality protocols are based upon recommended time dependent exposure limits which have been taken from various sources and standards for the primary pollutants of Carbon Monoxide (CO), Nitric Oxide (NO), Nitrogen Dioxide (NO_2) and Particulate Matter ($PM_{2.5}$ & PM_{10}). Table 3-1 below defines these exposure limits and the source of the recommendation. These limits are used to determine the ventilation requirement to keep air quality levels within the covered section to recommended levels. We note that the EPA and FHWA CO guidance is stated as being applicable up to an elevation of 5,000ft, with the project elevation being approximately 5,250ft this may require investigation further. An altitude correction for airborne pollutant concentration is provided by [33], applicable within the troposphere and accurate to 3%. The third column in Table 3-1 shows the influence that the 250ft difference in altitude has on the pollutant concentration limits applicable up to 5000ft. Using 5000ft as the altitude specific to the quoted limit, the resulting corrected limits for altitude demonstrate a very small reduction in concentration. In the context of Environmental Engineering considerations, the difference is negligible and will not be used further in this study.

Table 3-1 Pollutant Concentration Limits

Pollutant	Limit	Limit corrected for 5250ft altitude, assuming previous limit is a reference at 5000ft	Exposure Time	Source
Carbon Monoxide, CO	120ppm	118.88ppm	15 min	1989 EPA & FHWA guidelines
Nitrogen Dioxide, NO_2	1ppm	0.99ppm	10 min[3]	2012 PIARC
Nitric Oxide, NO	15ppm	14.86ppm	15 min	British Tunnelling Society
Particulate Matter, PM	0.007 m^{-1} extinction coefficient	-	-	2012 PIARC

3.1.1. Background Pollution Levels

The background (ambient) pollutants being brought in with the outside air, needs to be taken into account when calculating the in-tunnel pollution concentrations. PIARC 2012 [20] suggests CO may reach 5ppm and NO_2 may reach 200µg/m^3 for the background levels of urban tunnels but can be exceeded in dense urban tunnels. The background ambient levels assumed in these calculations are therefore 5ppm for CO and 0.08ppm for NO_2.

[3] PIARC suggest that as a tunnel passage generally only lasts a few minutes, stringent NO_2 threshold values should only be considered in combination with traffic conditions, such as congestion. A 10 minute exposure time has therefore been proposed for the 1ppm limit recommended by PIARC.

3.2. MOVES Modelling

In order to determine the total emissions produced by traffic in the covered section, a MOVES 2010b model was created. This is a simplified model using broad assumptions in order to determine the emissions levels within an order of magnitude to confirm that a proposed smoke control ventilation system design has the capacity to meet the required outside air demand. CDOT have provided project specific data for vehicle age distribution, source type distribution and meteorological information. The MOVES model concentrates on emission levels during congested traffic as this will produce the worst case conditions for pollution concentration levels. The input data and assumptions used are summarized in Appendix C and Appendix D.

The MOVES modelling estimates the volume of pollutants emitted at various traffic speeds in the covered section. In order to model worst case scenarios it is assumed that all lanes of the highway are at full congested capacity. MOVES input data used are specific to the I70 East region where possible. These data have been supplemented with Colorado State and Denver County data. These input assumptions will produce some error in the results compared to a full set of specific I70 East data inputs. However, such error is considered acceptable in the context of assessing the need for a conceptual ventilation system and its capacity estimation at this stage. The results of the MOVES modelling are given below in Figure 3-1. Pollution emissions have been calculated for the eastbound bore as it is the worst case due to road gradient which vehicles will have to drive up.

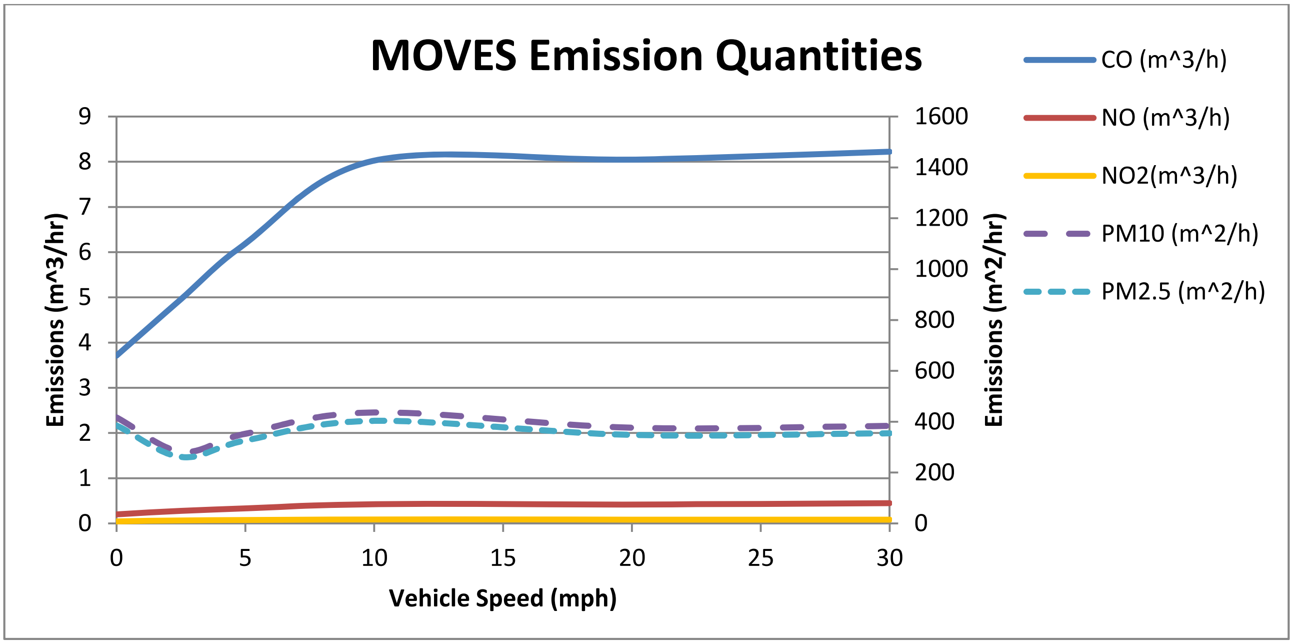


Figure 3-1 MOVES eastbound bore output results

An assessment for the need of a ventilation system to control air quality has been made on the basis of the time taken for the tunnel environment to reach pollutant exposure limits when traffic is at standstill. Exposure concentration levels vary with the exposure time period and in order to simplify this relationship a pollution exposure in ppm minutes is defined (product of the exposure level in ppm and the number of minutes of exposure at that level). The exposure limits given in Table 3-1 are used for calculation of limits in ppm minutes. Table 3-2 and Figure 3-2 to Figure 3-4 show the time taken to reach ppm minute exposure levels for CO, NO and NO_2.

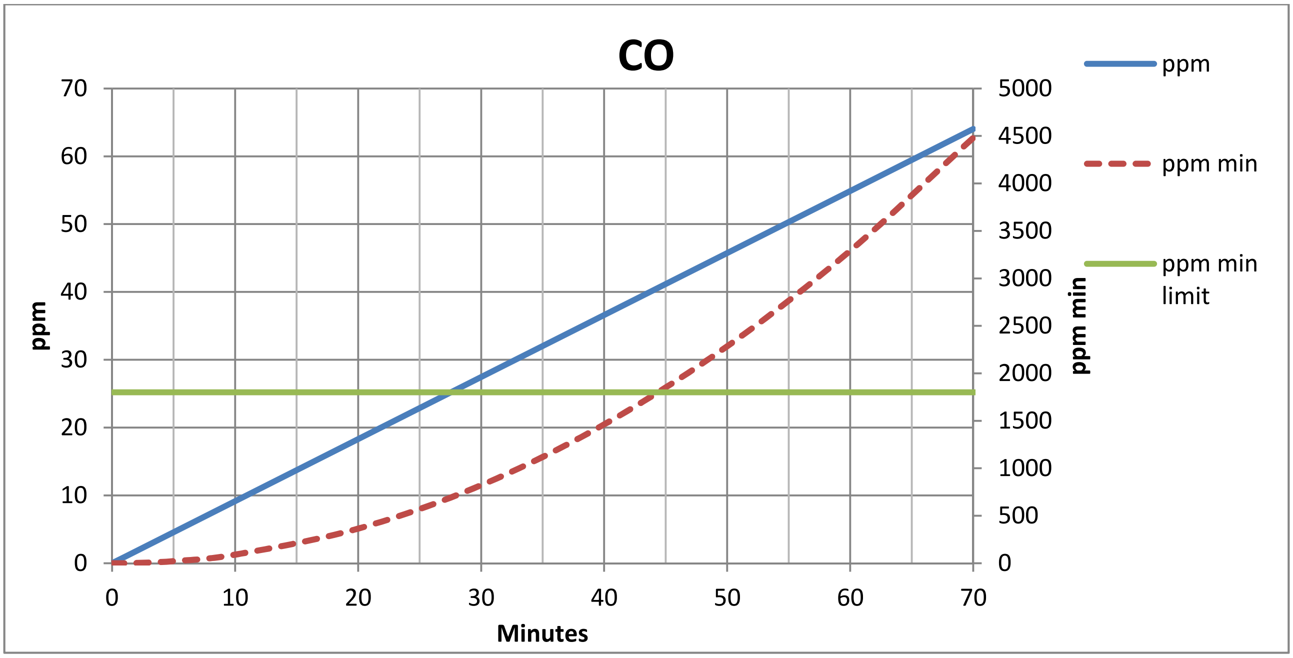


Figure 3-2 Time to reach CO ppm minute exposure limit

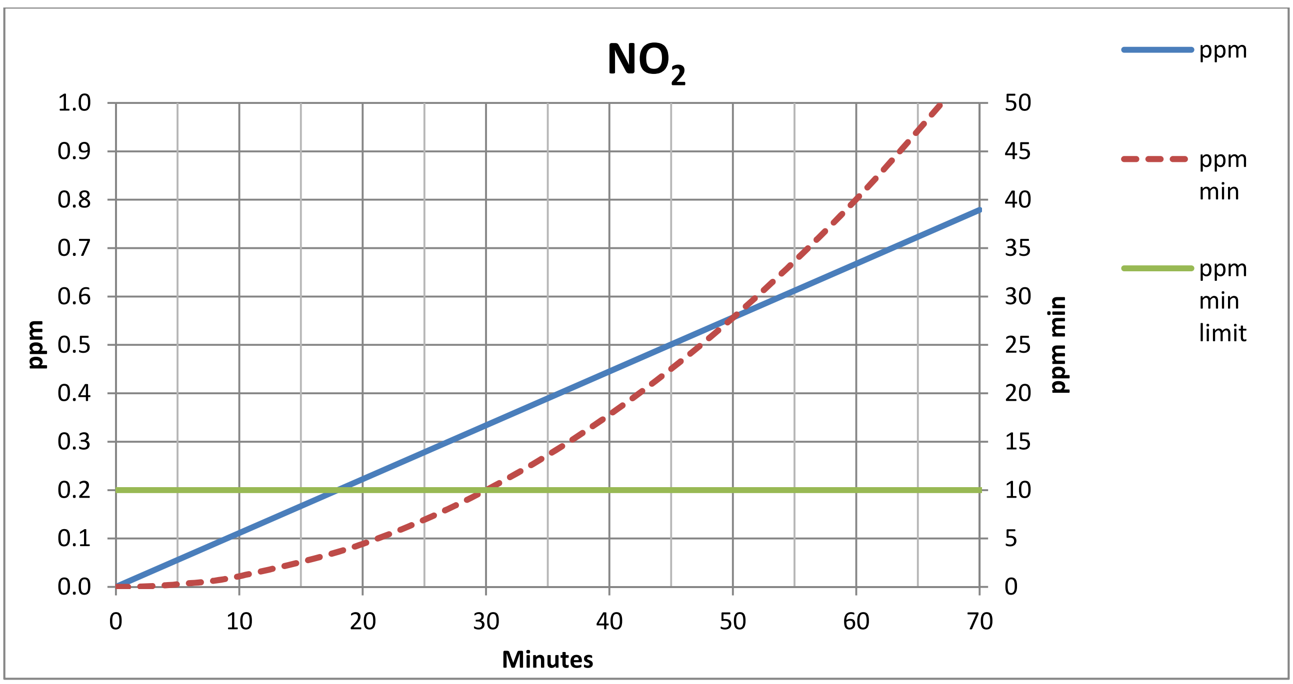


Figure 3-3 Time to reach NO_2 ppm minute exposure limit

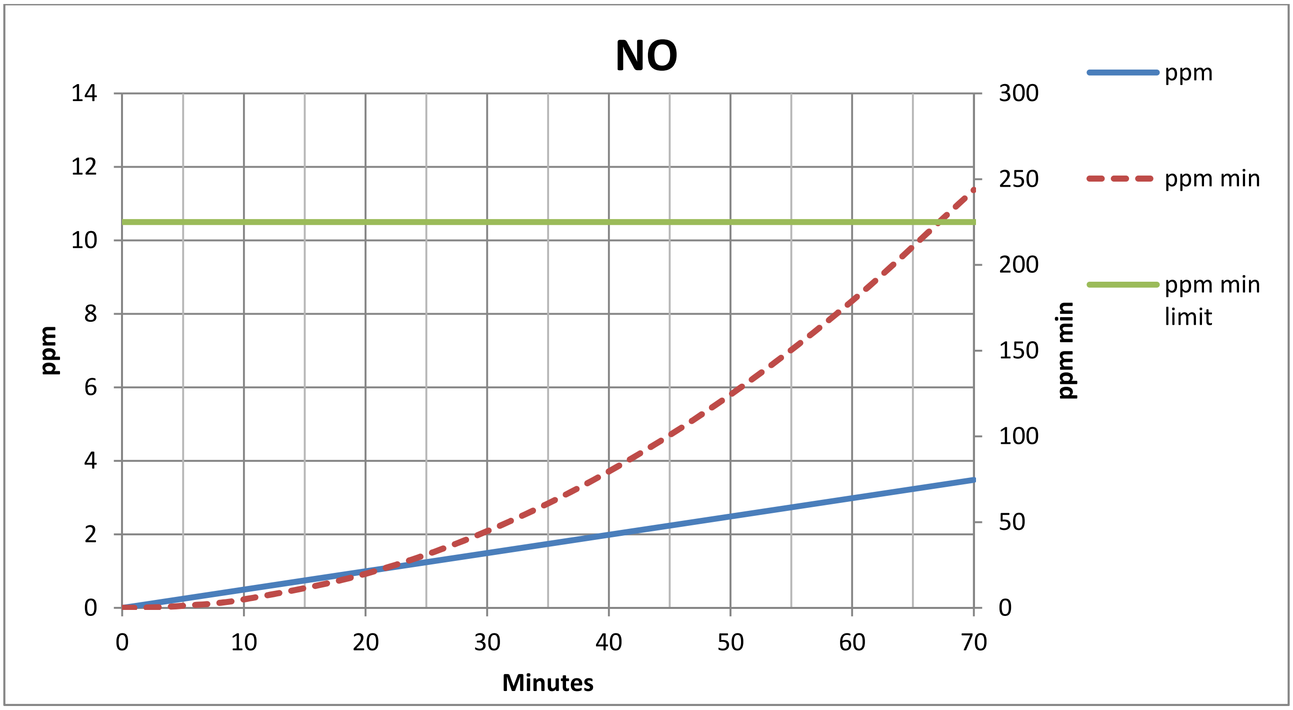


Figure 3-4 Time to reach NO ppm minute exposure limit

Table 3-2 Time to reach pollution ppm minute exposure limit

Pollutant	ppm min exposure limit (ppm min)	Exposure time to limit (min)
CO	1800	44
NO	225	67
NO_2	10	30

The results show that with stationary traffic in the tunnel and no significant portal pressure difference, the exposure limit for NO_2 would be reached first, taking about 30 minutes. This relatively short time indicates that a ventilation system is advisable for in-tunnel air quality control and is therefore recommended. Outside air needs to be induced into the tunnel by the ventilation system in order to reduce pollutant concentration levels. The volume of this outside air required is termed the Outside Air Demand (OAD), see 3.3.

3.3. Outside Air Demand

Table 3-3 below gives the guideline sensor limits and background pollution levels advised by PIARC [20] used in this study for calculating the volume of outside air that needs to be induced into the tunnel to control pollution levels.

Table 3-3 PIARC guidelines sensor limits and background levels

Pollutant	Sensor Limit	Background Level
CO	70ppm	5ppm
NO_2	1ppm	0.08ppm
PM	$0.07m^{-1}$	-

When traffic moves through the tunnel it induces an air flow due to the piston effect of the vehicles. At high enough vehicle speeds, this piston effect can provide the tunnel air flow required to meet the outside air demand. For traffic speeds below this the remaining outside air demand must be met by the ventilation system. Figure 3-5 below shows the outside air demand for the covered section and the flow induced by piston effect for the cases with 20Pa adverse portal pressure from wind effects and also with no adverse portal pressure (no wind). The 20Pa adverse external wind pressure comes from the 95th percentile easterly wind of 6.15 m s^{-1} (13.76mph) in E.1.2.

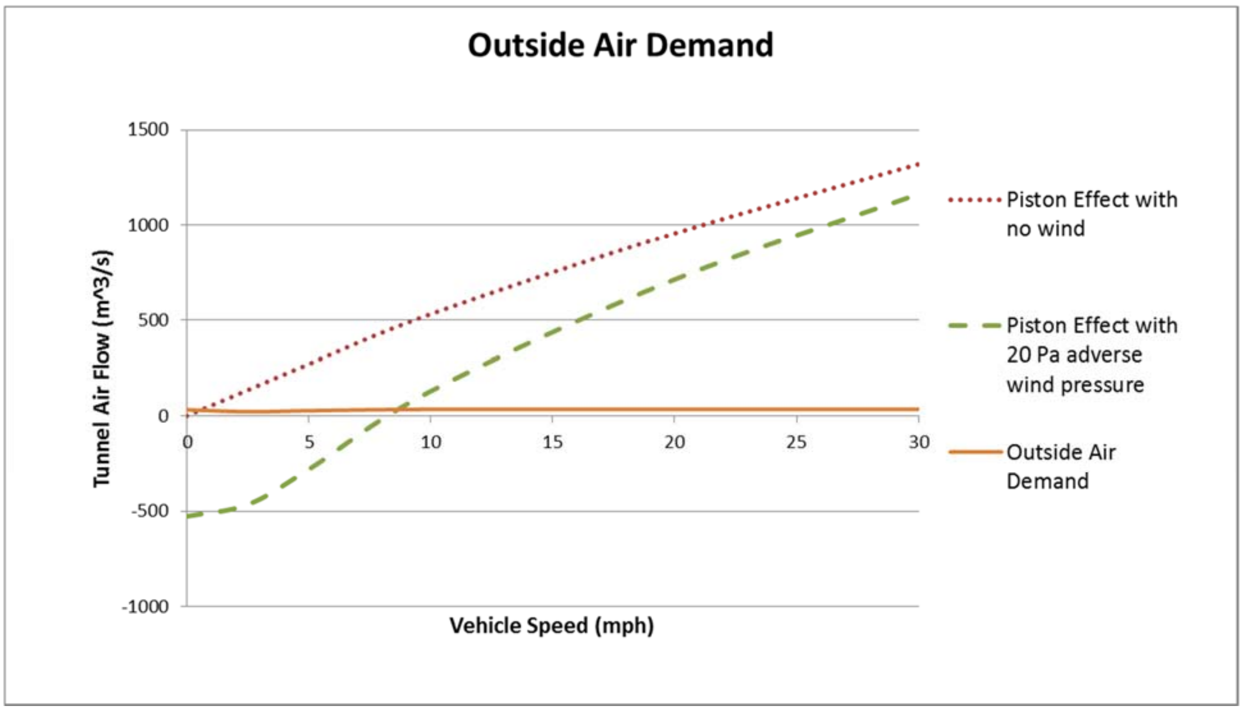


Figure 3-5 Eastbound bore OAD and Piston Effect

For vehicle speeds below where the piston effect lines cross the OAD line the ventilation system must provide the tunnel flow required. At low vehicle speeds the 20Pa adverse portal pressure wind effect induces a significant reverse tunnel flow. However, due to the transient nature of wind effects, this cannot be relied upon to provide the fresh air demand and the ventilation system must be able to overcome this and deliver a tunnel air flow in the traffic direction great enough to meet the OAD. The most demanding case for the ventilation system is therefore when there is an adverse portal pressure (in this case 20Pa) and the traffic is at a standstill and so there is no vehicle piston effect.

3.4. Portal Emissions

In order that pollution dispersion modeling can independently be performed by CDOT in the area of the covered section the total pollutants emitted from the traffic is required. The piston effect of the traffic flow will induce a net air flow through the tunnel in the direction of traffic as described previously. When the piston effect is not significant the tunnel ventilation system will ensure this net air flow in the traffic direction. The pollutants generated within the covered section will therefore be emitted from the exit portal of each traffic bore. The quantities of pollutants generated and emitted in each traffic bore have been calculated and tabulated in Table 3-4 for the predicted traffic volumes expected in 2035, identified here as the 'PCL ML Full Build' traffic and provided in Appendix D.

Table 3-4 PM and CO emissions from the PCL ML Full Build traffic

		PCL ML Full Build traffic							
		East Portal				West Portal			
From	To	PM10 (g/hr)	PM2.5 (g/hr)	Total PM (g/hr)	CO (g/hr)	PM10 (g/hr)	PM2.5 (g/hr)	Total PM (g/hr)	CO (g/hr)
12.00 AM	1.00 AM	3	2	5	300	2	2	4	188
1.00 AM	2.00 AM	1	1	2	119	1	1	2	75
2.00 AM	3.00 Am	1	1	2	119	1	1	2	75
3.00 AM	4.00 AM	2	1	3	179	1	1	2	113
4.00 AM	5.00 AM	5	4	9	479	4	3	7	300
5.00 AM	6.00 AM	20	16	36	1914	15	12	27	1200
6.00 AM	7.00 AM	62	48	110	5302	81	45	127	4136
7.00 AM	8.00 AM	108	75	182	7884	188	90	278	7497
8.00 AM	9.00 AM	76	57	133	6567	103	58	161	5473
9.00 AM	10.00 AM	44	35	79	5134	39	26	65	3287
10.00 AM	11.00 AM	36	27	63	4884	32	21	53	3126
11.00 AM	12.00 PM	36	27	63	5530	41	23	64	3800
12.00 PM	1.00 PM	38	26	64	6027	52	26	79	4313
1.00 PM	2.00 PM	35	24	59	5812	49	24	74	4159
2.00 PM	3.00 PM	39	27	66	6671	56	27	84	4775
3.00 PM	4.00 PM	52	31	83	6713	75	32	107	4856
4.00 PM	5.00 PM	65	40	105	8206	93	40	133	5935
5.00 PM	6.00 PM	81	46	127	7793	125	52	177	6338
6.00 PM	7.00 PM	58	41	99	6697	65	36	101	4814
7.00 PM	8.00 PM	31	24	55	3918	24	17	41	2398
8.00 PM	9.00 PM	19	15	35	2310	15	11	26	1414
9.00 PM	10.00 PM	18	15	33	2110	14	10	24	1291
10.00 PM	11.00 PM	15	12	28	1708	12	9	21	1046
11.00 PM	12.00 AM	6	5	10	598	4	3	8	375
Total		850	601	1452	96974	1093	573	1666	70984

4. Fire and Life Safety Requirements

4.1. Safety Objectives

The ventilation, fire and life safety requirements have been developed in line with NFPA 502, 2014 Edition and supporting international good practice based upon the following key safety objectives:

- Permit the users of the covered and sections of the I70 East highway study area to evacuate in reasonable safety;
- Reduce the life safety risk to as low as reasonably practicable;
- Allow fire department personnel to operate in reasonable safety.

4.2. Fire protection Requirements

The NFPA 502, 2014 Edition, Standard for Road Tunnels, Bridges, and Other Limited Access Highways clause 3.3.47 defines an enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals as being a Road Tunnel for fire protection and fire life safety purposes.

NFPA 502 standard provides guidance relating to the equipping of the tunnels in relation to their length and traffic flow. Using figure A.7.2 [1] from the Standard, a tunnel length of 999ft (~304m) and the worst case of a peak hour traffic volumes of 2294 vehicles/ hour per WB GP lane in the morning rush hour [11]; the covered section of highway would be classified as a category C tunnel (see Figure 6 below). Table 3-4 summarizes the foreseen fire life safety requirements and the relevant Standards. The full category requirements from NFPA 502 table can be seen in Appendix A.

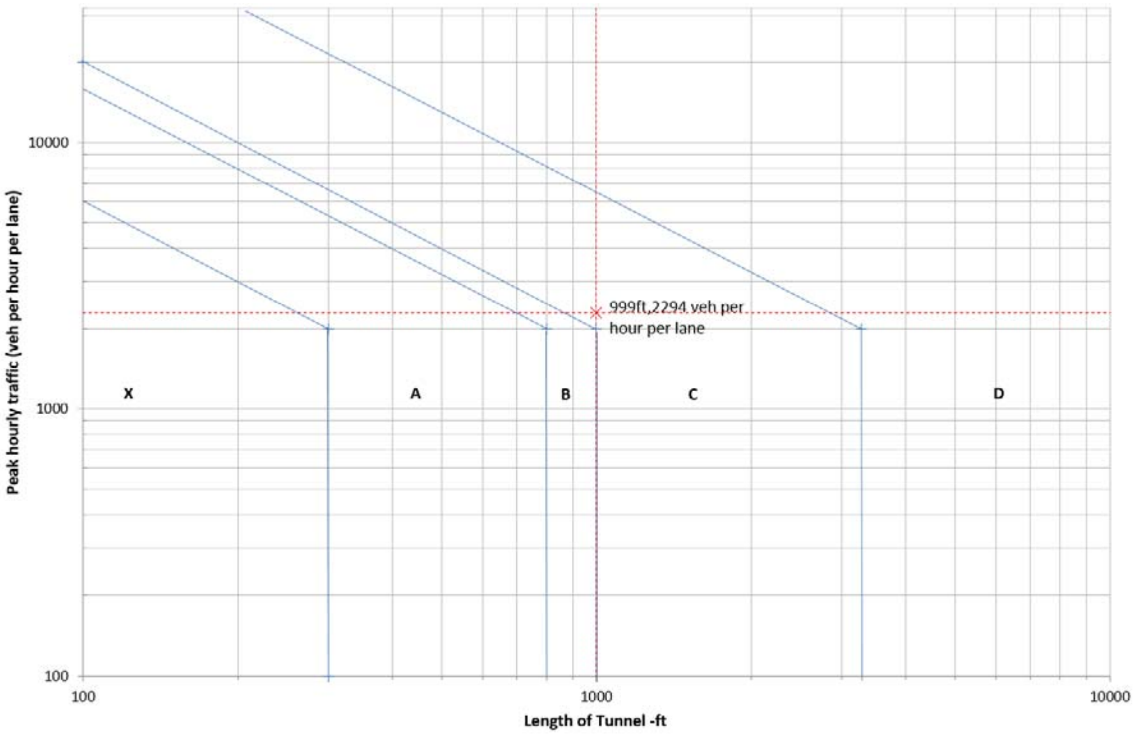


Figure 6 Urban and Rural Tunnel Categories (Based on NFPA 502 2014 edition, figure A.7.2)

Table 4-1 Covered section fire and life safety requirements

Item /requirement	Comments / reference standards
Structural elements protection	NFPA 502 and ASTM E 136-ASTM E 2652 or equivalent accepted by the AHJ for non-combustible material if structural fire protection material is provided.
Manual fire alarm boxes	NFPA 502 and installation, inspection and maintenance shall follow NFPA 72
CCTV	NFPA 502, shall be permitted as a fire detection means in tunnels with 24-hour supervision
Automatic fire detection.	NFPA 502 required if tunnel is not 24-hour supervised. It is also required when water based fire-fighting systems are installed and for ancillary spaces (e.g. pumps/ utility rooms). Installation shall follow NFPA 72 and approval from AHJ.
Fire alarm control panel	NFPA 502 and installation, inspection and maintenance shall follow NFPA 72.
Emergency communication systems	NFPA 502. Two-way radio communication enhancement systems. Installation, inspection and maintenance shall follow NFPA 72
Closure and traffic control	NFPA 502.
Standpipe, fire hydrants, and water supply.	NFPA 502, NFPA 14, NFPA 25, NFPA 22, NFPA 24. Fire department connections are mandatory. For hose connections follow NFPA 502, NFPA 1963 and the AHJ. Fire pumps are conditionally mandatory and for Installation, inspection and maintenance shall follow NFPA 20.
Portable fire extinguishers	NFPA 502, NFPA 10.
Fixed water-based fire fighting systems	NFPA 502. 'Conditionally' mandatory and shall be installed, inspected and maintained in accordance with NFPA 11, NFPA 13, NFPA 15, NFPA 16, NFPA 18, NFPA 25, NFPA 750 or other equivalent international standards acceptable to the AHJ.
Emergency ventilation	NFPA 502, 'conditionally' mandatory
Drainage	NFPA 502.
Hazardous locations	NFPA 502 and classification to follow NFPA 70, NFPA 820.
Hydrocarbon detector	NFPA 502.
Flammable and combustible environmental hazards	NFPA 502, 'conditionally' mandatory.
Means of egress	NFPA 502, NFPA 101 and Maintenance in accordance with NFPA 1.
Exit identification	NFPA 502.
Tenable environment	NFPA 502.
Walking surfaces	NFPA 502, NFPA 101 (Chapter 7)
Emergency exits doors	NFPA 502, and installed in accordance NFPA 80. Spacing between exits shall not exceed 300 m (1000ft) according to NFPA 502. It is proposed that given the number of traffic lanes and the potential for large numbers of people to be in the tunnel (and given that cross-connections may be made with relative ease) two cross-connecting egress paths will be appropriate, subject to approval of AHJ. The number of doors will be subject to further egress analysis during future option engineering stages.

Item /requirement	Comments / reference standards
Egress pathway	NFPA 502. The tunnel roadway surface when supported by traffic management system is considered as a part of egress pathway according to the standard. Emergency exits to be separated from the tunnel by construction enclosure having a class A interior finish following NFPA 101 and for pressurization to follow NFPA 92.
Electrical systems general, wiring and installation methods, emergency power, reliability and security plan.	NFPA 502 for all aspects except as follows: Fire resistive cables tested by the ASTM E 119 and functionality as per ANSI / UL 2196. For installed circuits embedded in concrete to follow UL 1724. For wiring methods NFPA 70, cables and conductors within cover to have reduced smoke emissions by methods suggested in NFPA 502 and tested by FT4 IEEE 1202 No. 0.3 or NFPA 262 or CSA FT6 or equivalent international standards accepted by AHJ. Cables, conductors, raceways, equipment and supports tested in accordance with MIL-C-24643. The installation methods to follow NFPA 502 or approved by the AHJ. Emergency power in accordance article 700 of NFPA 70, and for emergency and standby power systems other than separate service refer to NFPA 110.
Emergency lighting	NFPA 502, NFPA 70, NFPA 110, NFPA 111.
Exit signs	NFPA 502.
Lighting for natural conditions	FHWA document section 4-11[13], CIE 88-2004.
Emergency Response	NFPA 502 for most aspects, and for the Operations Control Center (where applicable) to be a proprietary supervising station to meet NFPA 72. Emergency incidents to be managed in accordance with NFPA 1561.

NFPA 502 (2014 edition)

4.3. Covered Highway

NFPA 502 clause 4.3.5 states that standpipe systems or fire extinguishers, or both shall be installed on depressed highways where physical factors prevent or impede access to an acceptable water supply. We recommend, subject to agreement by the AHJ, that a standpipe system protected against the risk of freezing in winter along with fire extinguishers suitable for vehicle fires housed within purpose made and alarmed cabinets be provided. The planned I70 East project will be equipped with CCTV cameras to facilitate the management and control of the highway including the covered and depressed sections. The monitoring of the highway is an important part of any operational risk management plan as it will assist emergency services in responding to an incident in the shortest possible time.

4.4. Structural elements protection

NFPA 502 clause 7.3 requires the cover structural elements be designed to support fire fighter accessibility, mitigate damage; prevent collapse and minimize economic impact upon tunnel closure in the event of a fire. Evidence of performance of fixed fire-fighting could be used for protection of the structural elements to a degree but such evidence has to be provided and approved by the AHJ. The requirement for any fixed or active fire protection systems should be considered in line with the guidance provided within the standard. Recommendations over structural fire protection are outside the scope of this report.

4.5. Fire alarm and detection in covered section

The covered section of the I70 East being classified as Category C requires at least one manual means of identifying and locating a fire. Should the covered section also not be supervised on a 24-hour basis or if fixed fire-fighting is installed in the cover section an additional requirement will apply, that of an automatic fire detection system. For the manual fire alarm system these are manually operated fire alarm boxes located within the covered section at intervals of no more than 90m (300ft) and at all cross-passages and points of egress, that is portals. For those facilities with 24-hour supervision CCTV can be used for the purpose of identifying and locating fires. Should automatic fire detection systems be required, the system shall be capable of detecting an early stage fire within 15 m (ft) and zoned in accordance with the covered section ventilation and or FFFS zones.

4.6. Communications in covered section

Two-way radio communication enhancement systems are conditionally mandatory for the covered section given its Category C status. It is foreseen that given the number of traffic lanes and the potential for large numbers of people to be in the tunnel the Radio communications are required by the fire department together with a system to permit break-in to local radio channels for direct communication with motorists. Telephones of the outdoor-type may be required subject to the AHJ requirements.

4.7. Traffic Control in covered section

Means to stop traffic entering the direct approach to the covered section, to control traffic within and clear any traffic exiting downstream the fire site following activation of a fire alarm are required. These typically take the form of lane use signals with green downward pointing arrows, 45 degree arrows if lane changing is required or a red cross if the covered section is closed to traffic. Variable message signs at the portals can support motorist compliance and aid information flow. We would recommend that specific covered section traffic control measures are extended beyond the portals to assist with stopping traffic upstream of the fire site in line with the requirements of NFPA 502 clause 7.6.2. When closing approaches this should be done in such a manner that responding emergency services vehicles are not impeded to the fire site.

In cases where it is not possible to provide means to dispatch vehicles downstream of the incident and in the non-incident section measures need to be taken to provide a safe and tenable evacuation route of motorists which may include fixed firefighting system.

4.8. Fire protection in covered section

Standpipes, fire hydrants and water supply are to be provided in line with NFPA 502 requirements. Trace heating and other measures shall be considered for wet pipes and fittings exposed to freezing. Three to four portable fire extinguisher cabinets will be required at intervals of not more than 90m (300ft) along the central partition between tunnel bores on both carriageways. Given the unusually high width of the tunnel, consideration may be given to additional cabinets on the outer walls of the tunnels, subject to agreement with the AHJ.

The water supply arrangements will vary dependent upon local conditions prevailing at the portals and at an early stage of design those conditions will need to be assessed and discussed with the AHJ to establish an acceptable approach. Options include connection to a water supply providing the required flow and pressure; fire pumps connected to an approved water source or independent water storage gravity or pump feed. The covered section will require a specifically designed drainage system to meet the requirements of NFPA to prevent the spread of spills from hazardous and flammable liquid spills and water originated from fire-fighting systems in place.

The drainage system and any storage sumps/tanks will need to be equipped with hydrocarbon detection and possibly foam inerting systems to prevent explosions. The cover would also require an engineering analysis of potential fire life safety hazards originating from naturally occurring and constructed environmental hazards. In regards hazardous materials that go through the cover they shall be regulated by the AHJ and its fire size, growth rate and smoke generated can be reduced where a design analysis can show pool size is limited by road design (e.g. slope and drainage design). It is understood at present that hazardous materials (HazMat) will not be restricted from the route, however the nature of specific materials or quantities are still unknown at the current stage of conceptual design.

4.9. Means of egress in covered section

Emergency exits (including cross-passageways) are required under Category C to the adjacent bore separated by a minimum 2-hour fire-rated construction. This is considered an acceptable alternative to exits to open air. These are provided to minimize the user's exposure to an untenable environment. The spacing between exits may not exceed 300m (1000ft). Exit doors shall provide protection against fire and ensure pressurization of escape routes they shall be 1 ½ hour rated. Given the tunnel category and the number of lanes (the full build case that includes 6 lanes in total, 3 GP lanes, 2 managed lanes -toll lanes- and a ramp), to evacuate the potentially large numbers of people and provide an access route for the fire department it is foreseen that at least 2 cross-passageways should be provided in the covered sections, equally spaced. The use of cross-passageways to the non-incident bore will require operational management plans to stop all traffic operations as soon as practicable in the non-incident section of highway to minimize the risk to evacuees and fire department personnel.

The tunnel roadway surface, when supported by a traffic management system, is considered as a part of an egress pathway according to NFPA 502.

4.10. Electrical

The electrical system is required to support all life safety operations during fire emergency operations and normal operations and shall follow NFPA 502 requirements. These cover such elements as: ventilation system, lighting (for normal operations and emergency), fixed firefighting system (if implemented), exit signs, traffic control, drainage, fire alarms, CCTV. Redundancy and emergency power requirements will also need to be provided as part of the overall design and construction.

Lighting of the highway to ensure drivers can see obstacles, conduct manoeuvres and stop safety in the covered section at any time of the day or night is a critical safety measure in reducing the frequency of incidents and accidents. Dependent upon length, the covered section may require several daytime lighting levels- one intensive zone at entry followed by a transitional zone and a covered section interior zone. Lighting levels are set to match the human eyes adaption to changes. The lighting design will need to consider emergency situations to ensure adequate lighting levels and uniformity are provided for the roadway and walkway surfaces [4].

4.11. Fixed Fire Suppression Systems

Whilst the use of a water based fire-fighting system, examples of such being low-pressure deluge and mist suppression, is a conditionally mandatory requirement its use could have specific advantages when considered as part of an Engineering Analysis together with an emergency ventilation system. Such a system is proposed at this stage and subject to approval from AHJ (refer to Partial Covered Lowered Lid Section Design Fire Size technical note).

By implementing such a system the size of the ventilation system could be reduced to operate in harmony with the suppression system and other safety measures in the covered section in order to achieve an equivalent level of safety when compared to a system with no suppression and higher ventilation specifications (see 5 and Partial Covered Lowered Lid Section – Design Fire Size technical note). Again this is subject to approval from AHJ. Additional implications of having such systems is the need of an automated fire detection system and the consideration of increased drainage requirements as indicated in 4.5 and 4.8 respectively.

4.12. Emergency Ventilation requirements

Chapter 11 of NFPA 502 2014 sets out the requirements for emergency ventilation, if applicable, for a covered section of highway. Clause 11.4,1 notes "The design fire size (heat-release rate produced by vehicle (s)) shall be used to design the emergency ventilation system."

NFPA 502 (2014) is not prescriptive in its specification of design fire but states that the defined fire scenario for emergency ventilation will be based on the operational risk associated with the type of vehicles expected to use the tunnel. The Standard refers to test data from heavy goods vehicle fire tests reaching average peak heat release rates of up to 200MW with times to reach peak heat release rates from 7 to 48 minutes[4], and for flammable combustible liquid tankers suggests a representative 300MW. NFPA 502 states that the design fire is not necessarily the worst fire that may occur but that engineering judgement is required to be used to establish the probability of occurrence and the ability to achieve practical solutions.

Based upon the above an assessment has been made based on standard and current good practice analysis, the likely return periods for fires of different severities[5], analysis of geometry, evacuation timeline and the use of FFFS to conclude on a reasonable fire size proposal for the I70 covered section (see 5) .

4.13. Emergency response

Emergency operations input is to be sought during planning, design and construction stages of the covered section. An emergency response plan is required so is available to all pertinent parties and shall be created and submitted for acceptance by the AHJ for various incidents listed in NFPA 502 including fires or smoke conditions involving one or more vehicles in the cover or it adjacent zones and hazardous materials accidentally or intentionally being released into the cover. Training programs (including exercising and drills) should include all aspects considered within the emergency response plan.

5. Design Fire size

The design fire size (the peak heat release rate in MW) provides the fire characteristic used to inform the design sizing and configuration of the tunnel fire safety equipment and facilities. Design fire criteria are also required for the protection of the I-70 Cover structure; although these considerations are outside of the scope of this document.

NFPA 502 (2014) is not prescriptive in its specification of design fire but states that the defined fire scenario for emergency ventilation will be based on the operational risk associated with the type of vehicles expected to use the tunnel. The Standard refers to test data from heavy goods vehicle fire tests reaching average peak heat release rates of up to 200MW. NFPA 502 states that the design fire is not necessarily the worst

[4] Values taken from table NFPA 502 table A.11.4.1 from the time to peak HRR (min) column, experimental times to reach peak heat release rates vary.
[5] This is done using a statistical approach with tunnel and traffic data; and expected fire rates, as defined in Appendix B item B.2.2.

fire that may occur but that engineering judgement is required to be used to establish the probability of occurrence and the ability to achieve practical solutions.

The assessment method for the proposal of a reasonable tunnel design fire for ventilation and fire life safety aspects is based on various factors listed below and detailed in technical note titled Partial Covered Lowered Lid Section – Design Fire Size:

- Current standards and good practice;
- Fire likelihood (based on traffic mix, vehicle characteristics and tunnel operating mode);
- Tunnel geometry;
- Timeline for evacuation and;
- The used of FFFS.

The I70 Cover is classified under NFPA 502 (2014) as a Category C Tunnel, requiring commensurate fire safety provisions including consideration of fixed fire fighting systems and mechanical ventilation. NFPA 502 suggests a fire size of 300MW when a flammable/combustible liquid tankers are considered. Based on engineering analysis, a 300MW fire event (which may be explosive) is predicted to have a sufficiently long return period (in the order of once every 30,000 years) to fall outside of what is considered a reasonable design case for this project. Further details of the fire frequency analysis can be found in Appendix B.

Standards and good practice alone would indicate a representative design fire load of 150 MW is appropriate, in general, for the ventilation design for a road tunnel in the US. UK and US practice for new and recently refurbished tunnels have adopted 100MW as a design fire load in the absence of a fixed fire fighting system (FFFS). Analysis shows that a design for fires of up to 150MW is shown to be sufficient to cover 99.9% of fires predicted to occur in the I-70 Cover. Research has shown that tunnel geometry and particularly width would have an influence on the potential peak heat release rate of a severe fire. A potential 150MW fire is shown to be more likely to be limited to a peak heat release rate of 120MW when considering the specific geometry of the I-70 Cover.

Fire growth characteristics and evacuation timelines are shown to be as critical as overall fire peak heat release rate. Given appropriately conservative assumptions for parameters affecting these aspects, for the potential 120MW fire at an ultra-fast growth rate, the I-70 Cover would be expected to have been evacuated within 9-minutes, when the fire is at a HRR of 55MW. By this time it is expected that the fire department would be on-site at the covered section. FFFS has the potential to limit fire growth and reduce the convective heat load to be managed by the ventilation system. NFPA 502 states that if a FFFS is installed the AHJ can reduce values for HRR for design purposes based on an engineering analysis considering the system activation time, resilience and reliability.

Although ventilation design for 55MW convective load is possible within the constraints of the I-70 Cover project, such design would require larger and/or more jet fans with commensurate additional noise and power requirements. With the implementation of a FFFS there is potential to reduce the design fire load for the ventilation. For a potential 120MW fire, appropriately designed FFFS will be expected to limit fire growth to a total HRR of 60MW. The convective proportion of this residual HRR that is required to be managed by the longitudinal ventilation system is estimated to be 50% of this value, 30MW (see summary flow chart below in Figure 5-1).

Design and development of specifications for FFFSis to proceed on this basis pending approval of the AHJ. FFFS offers the additional benefits associated with the support of fire fighting, protection of the structure and equipment of the I-70 Cover during a fire and enabling the more rapid re-opening of the tunnel; limiting associated traffic delays and maximising availability.

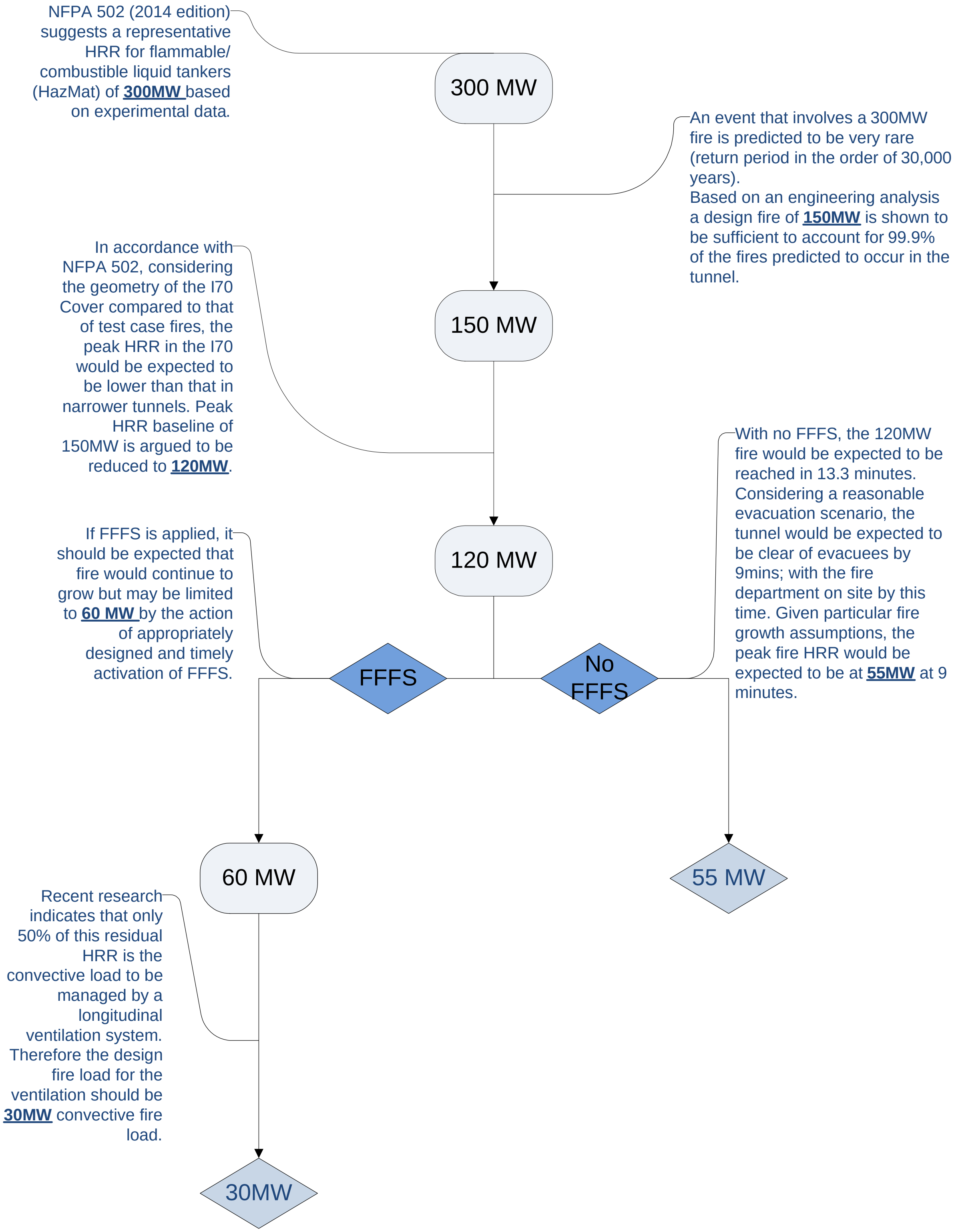


Figure 5-1 Flow chart summarising the aspects considered for defining a design fire for the I70 covered section

6. Conceptual Fixed Fire Fighting System (FFFS) Design

6.1. Objectives

The conceptual fixed fire fighting system design in the covered highway section has the following design objectives based on NFPA 502:

1. To slow, stop or limit fire growth, limiting residual convective heat release to be handled by the ventilation system;
2. To mitigate the impact of fire to improve the tenability of the environment for evacuation and;
3. To aid fire fighting operations.

These are outlined in the following sections:

6.1.1. Control fire growth

Fixed Fire fighting systems have shown to be successful in slowing fire growth and preventing fire spread. The effectiveness in limiting fire heat release is dependent on the nature of the fire load, the time-line for fire growth and suppression activation and the degree to which the fire is shielded from the suppressant. The system is categorized following NFPA 502 as a *Fire Control System* defined in 9.2.2.2.:

> *Fire control systems shall be design to stop or significantly slow the growth of a fire within a reasonable period from system activation such that the peak heat release rate is significantly less than would be expected without a fixed fire fighting system.*

The impact of the FFFS would affect the sizing of the emergency ventilation system.

6.1.2. Aid Evacuation

It has been demonstrated that fire suppression systems in road tunnels can be effective in reducing temperatures in the vicinity of the fire, and reducing fire growth. Fire fighting systems have also been shown to effectively attenuate radiation by screening the radiant heat from the fire.

If temperatures, heat flux, fire growth rate and smoke production are reduced, the tenability for escape would be expected to be improved as shown by the SOLIT2 tests [39].

Figure 6-1 below illustrates the expected benefits of fire suppression systems in the I70 covered section; given the way that ventilation is currently proposed at this stage (i.e. longitudinal ventilation via jet fans). Further details about ventilation concept are given in section 7.

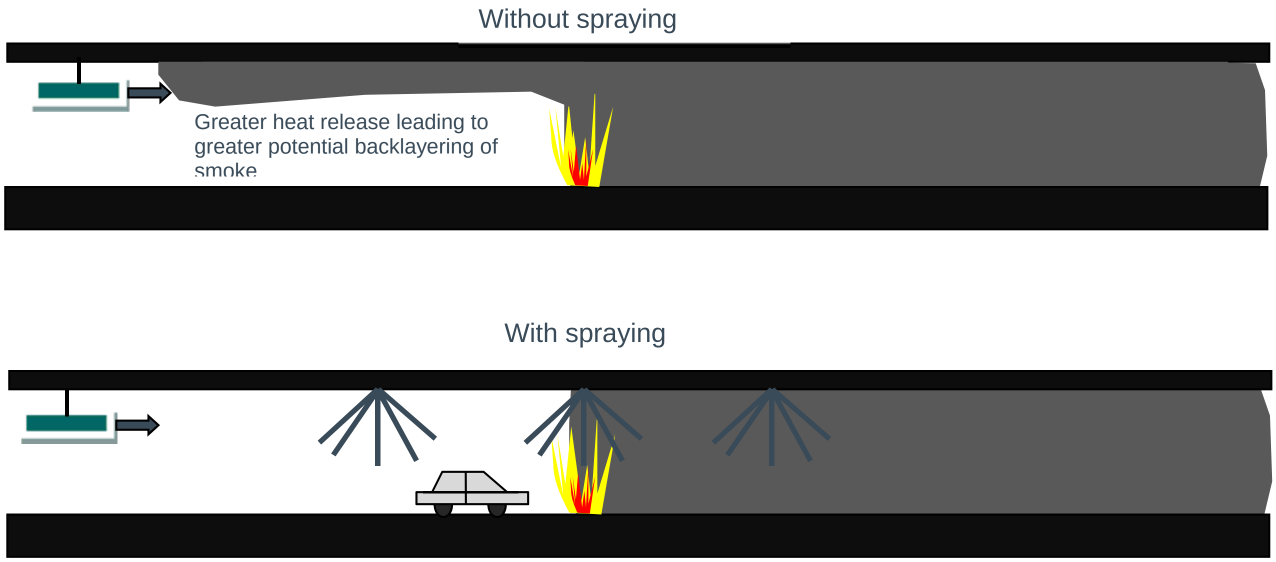


Figure 6-1 Illustration of suppression benefits in the I70 cover

In the covered section, the fire fighting system would be expected to control heat release rate so that the longitudinal ventilation is adequate to push smoke downstream where there are no tunnel users. Fires with the potential to over-power the ventilation system may therefore be controlled so that the ventilation is adequate to limit backlayering. Early activation of fire suppression is recommended.

6.1.3. Support of Emergency and Fire Fighting Services

The ability of fire fighters to attack a fire in the I70 covered section will be largely dependent on the fire size at the time they arrive at the site. Fire service response time in Denver has been advised by Denver Fire Department[6] as following the NFPA 1710 standard of 4 minutes from being on route to site (to which the alarm and mobilisation time would need to be added). An ultrafast growing fire (as shown on the technical note Partial Covered Lowered Lid Section - Design Fire Size and Figure 6-2 below) could be releasing heat at a peak rate of 70MW within about 10 minutes. Under these circumstances, the prior successful activation of a fire suppression system, before the fire starts its ‘rapid growth phase’ could contain the fire at a lower heat release, the smoke from which would be manageable by the ventilation system; therefore providing a more tenable environment for the fire service to attack and extinguish the fire.

The SOLIT2 guidance [40] indicates that reports based on anecdotal experience for larger fires without FFFS approach to a distance below 50 m is not possible; when compared to a mist system where the high cooling effect and the absorption of radiant heat make it possible to get closer to the fire source.

[6] Communication between Atkins and the Division Chief of Technical Services (see technical note Partial Covered Lowered Lid Section Design Fire Size)

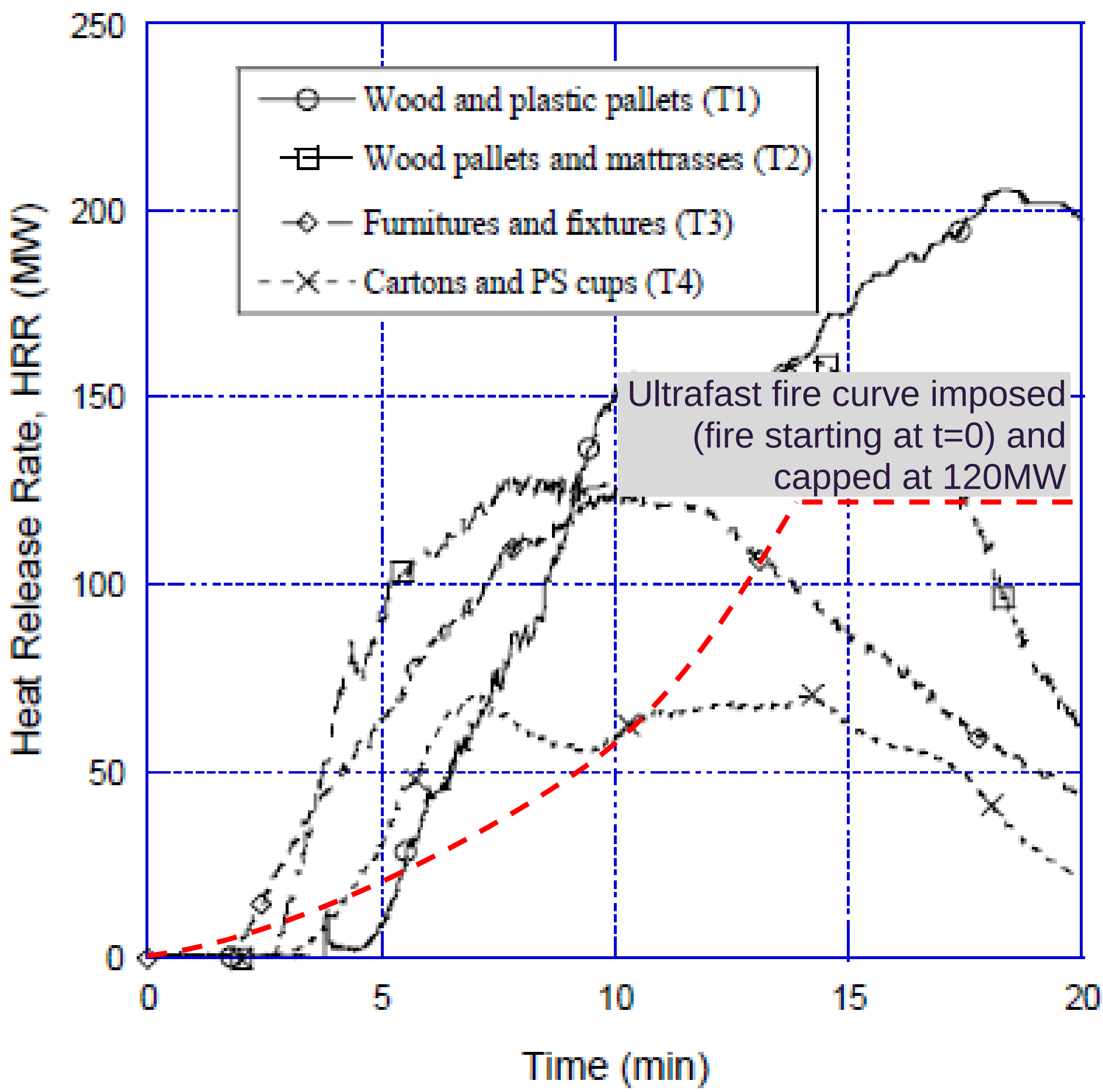


Figure 6-2 HRR data from Runehamar up to 20mins with superimposed coloured line for corrected fire size by geometry assumptions for the I-70

6.2. FFFS Concept

6.2.1. System Type

There are various types of water based suppression systems, distinguished by their droplet size and whether or not they introduce foam. Water-based systems aim only to suppress fire and not to extinguish it. They typically work by a system of pipes with a fixed water supply (i.e. a dedicated reservoir), which discharges water directly onto the fire and the surrounding area in order to suppress the fire and cool the neighbouring areas. The introduction of foam provides additional benefits, particularly where large liquid fuel fires are a significant risk. Two main class of system are considered here, classified according to droplet size and system pressure:

a. Low pressure deluge
b. High pressure mist

Engineering guidance from SOLIT2 [40] describes general methods to consider the following aspects as minimum when deciding the type of system to go for:

a. Fire Risk
b. Level of protection
c. Other safety measures available
d. Geometry
e. Ventilation/Wind conditions during a fire and interaction with the selected FFFS
f. Type and performance of the fire detection systems
g. Activation mode of the FFFS
h. Space restrictions for equipment (i.e. nozzles)
i. Distance to emergency exits
j. Signage and lighting
k. Thermal conditions
l. Any Other specific requirements

6.2.1.1. Low Pressure Deluge

The term 'deluge system' is often used to describe a more traditional sprinkler-type system which releases larger droplets at a higher flow rate and lower pressure than 'mist' systems. With deluge systems, the main pipework is typically fully charged ('wet') up to the section valve so that, on fire detection, the nozzles in the activated section may be quickly filled with water. Main distribution pipes are therefore typically fitted with trace heating. On confirmation of fire, nozzles in a number of zones (often three zones of about 25m) are simultaneously activated, discharging spray onto the fire zone and adjacent zones. The higher flow rate of low pressure deluge systems (compared to mist systems) requires careful consideration of water supply and drainage requirements, in particular in the case of the I70 as the volume to protect would be large given the tunnel width compared to other tunnels where these systems have been installed. These types of system are routinely installed in road tunnels in Australia and Japan.

6.2.1.2. High Pressure Mist

Water mist systems eject relatively small amounts of water at high pressures from specially designed nozzles. The small droplets provide a mist with a relatively large surface area which results in an improved heat transmission from the fire to the water, allowing the water to be evaporated more rapidly and efficiently than systems that generate larger droplets. The effectiveness of a system can rely heavily on the choice of pressure and droplet size and can vary from tunnel to tunnel depending on the ventilation regime and tunnel geometry. Mist systems also typically operate in 'deluge' mode, whereby a number of nozzles are activated simultaneously in a predefined zone. High pressure mist systems have been installed in a number of tunnels worldwide.

A sketch of a deluge-type mist or sprinkler system is shown in Figure 6-3 below.

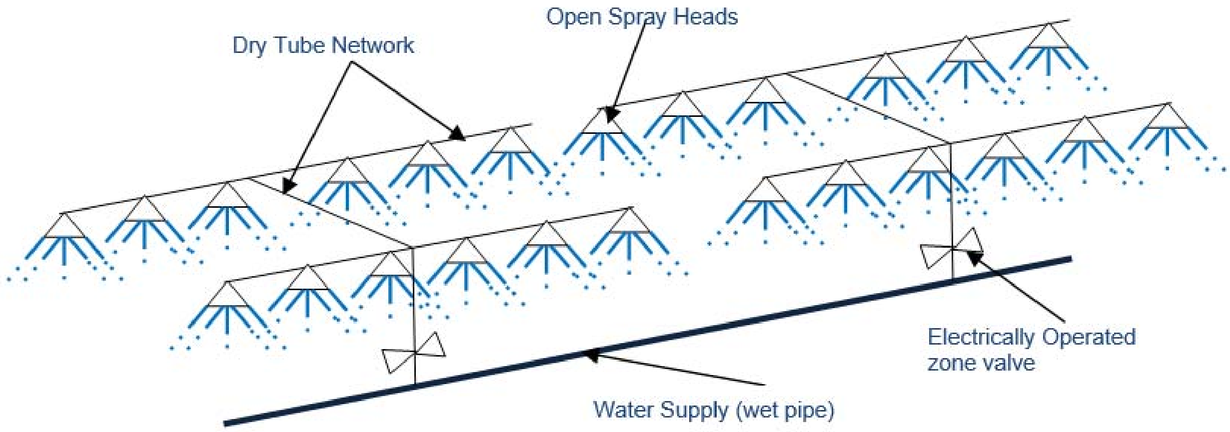


Figure 6-3 Sketch of zoned Fixed Fire Fighting system [41]

6.2.2. System requirements

Both water mist and low-pressure deluge suppression systems require water supplies and associated pumps, control and detection equipment, some of these elements will need a plant room to be located at a distance not far from the cover section. The sizes and ratings will depend on the system used and the performance specifications of the system. The major elements of the system to be considered are as follows:

a. Water supply
b. Drainage
c. Pumping and Pipework
d. Power

6.2.2.1. Water Supply

With regard to types of supply water, SOLIT2 guidance [40] defines the supply as a system consisting of a water reservoir, a pump system, pipework and section valves. The water supply and discharge requirements may be specified in terms of a flow per ground surface area of protected space (i.e. in $l/min/m^2$). Typical water consumption per volume unit could be around $2\text{-}4l/min/m^3$ for a large droplet system and between 0.2 and $1l/min/m^3$ for a water mist installation according to PIARC [41]. Based on these numbers and assuming 3 zones protected of 25 meters each this would equate to a water consumption in the order of 30,000 – 60,0000 l/min for a deluge system and 3,000- 14,000l/min for a water mist system. These values are indicative only and subject to detail design from the manufacturer. The flow rates together with system pressure and running times would dictate the tank and pipeline sizes.

6.2.2.2. Drainage

Drainage systems dimensions should consider the maximum flow rate of the FFFS in addition to other I70 requirements. In the case of additives, their collection and disposal should be also included. Pump stations should have a drainage capacity that equates as a minimum as the water supply flow rate (see water supply section above).

6.2.2.3. Pumping

Guidance is provided in the SOLIT2 documents, and the system should be dimensioned to provide as a minimum 110% of the nominal flow required for the most demanding protected area. This volume flow requirement can be provided by one or more pumps.

6.2.2.4. Power

Power supply for a FFFS should have the same level of reliability as required for ventilation and main control system. The power requirements would depend upon the system design (i.e. flow and pressure requirements for the most demanding section) and can be significant.

6.2.3. Performance specifications

Although there is a high level of research and testing of active suppression systems in tunnels, there is not yet consensus on what constitutes acceptable minimum performance for water-based fire suppression systems. However, suitable approaches to performance specification have been developed for recent projects and have proven acceptable to leading suppliers in the FFFS market.

The fire size technical note (Partial Covered Lowered Lid Section – Design Fire Size) has highlighted FFFS is recommended for the I-70 Cover to limit fire growth to a peak of 60MW; and to further limit the residual convective heat release rate seen by the ventilation system to 30MW. Design and development of specifications is to proceed on this basis pending approval of the AHJ.

6.2.4. Operational concept

Automatic fire detection may be through a combination of video automatic incident detection (AID), linear heat detection system and direct operator intervention. Detection may also be manual, through tunnel user or operator observation. In order to instigate a delayed-automatic operation of suppression (a countdown) two separate means of detection may be required to be confirmed; one of which can be the linear heat detection system which identifies the fire location. As the system is usually zoned (i.e. for the 304.5 meters covered section of the I70 the system would equate to 12 zones of 25 m each). The operating principle is usually to operate three zones (fire location and one zone upstream/downstream the fire). Details of activation times, running times, etc. will be defined at later stages depending upon system design, specifications and agreement on operational matters with key stakeholders (e.g. fire department, operator, CDOT etc).

7. Conceptual Ventilation System Design

7.1. Objectives

The conceptual ventilation system considered in the covered highway section has been selected to achieve two design objectives:

1. Control pollution concentration levels (air quality) during normal and congested operation within the covered section;
2. Control of smoke and hot gases in the event of a fire (emergency operation).

The scope of work for each of these objectives is outlined in the following sections.

7.1.1. Maintenance of air quality

The air quality within the cover section is reduced by vehicle emissions. The primary pollutants of interest are nitrogen dioxide (NO_2), carbon monoxide (CO) and particulate matter (PM). The generation rates of these emissions are calculated using an industry-standard approach, where fleet composition, vehicle speed, traffic density and road gradient are taken into account (see Appendix C). The polluting effect of vehicle emissions can be counteracted by a flow of relatively clean outside air through the I70 covered section. The flow rate of outside air required to dilute pollutants to acceptable concentrations ('outside air demand'), may be induced by vehicle motion (the 'piston effect') or by the tunnel ventilation system.

The most onerous condition for the tunnel ventilation system to control pollution levels is when there is 20Pa adverse portal pressure and the tunnel is full of standstill traffic and so no piston effect is created. Under these conditions the smoke control ventilation fans with just 6 jet fans running is able to induce a tunnel air flow of 188.4m^3/s (399,220 CFM). This volume flow is significantly in excess of that required for pollution control (see 3.3). In actual operation the management system would control the number of fans and fan speeds in operation so that only the required tunnel flow is induced. The excess ventilation capacity for pollution control gives a level of comfort when considering the degree of accuracy in input data that the MOVES model was created with.

7.1.2. Smoke control

For fires during free flow traffic conditions, the smoke control strategy is to activate FFFS at the fire location to limit fire growth and convective heat release rate; and to ventilate and move smoke in the direction of traffic flow. It is assumed that vehicles ahead of the fire are free to leave the tunnel unhindered, while there might be vehicles trapped behind (upstream of) the incident. When no vehicles are situated downstream of the fire, the strategy is to use all available fans to push the smoke out of the exit portal. The primary function of the emergency ventilation is to prevent smoke propagation back over the stopped vehicles upstream by creating a longitudinal ventilation velocity in the covered section that exceeds the critical velocity. When critical velocity is not achieved, back layering of smoke against the ventilation direction occurs. A variation to this strategy occurs for an incident in the vicinity of the entry portals were fans may be destroyed by the fire. For this scenario, the only people in the tunnel will be those stopped in the short section between the entry portal and the fans. It is assumed, due to low number of people involved and short escape distances, that those people will have exited the tunnel during the early self rescue phase of any tunnel incident.

The design objective of control of smoke and hot gases can be achieved when the minimum air velocity required to overcome the buoyancy of smoke (critical velocity) is met. The critical velocity is calculated by balancing momentum in a one-dimensional control volume around the fire [28]. The ventilation system must induce an air flow at critical velocity while overcoming hydraulic losses (e.g. wall friction, vehicle drag etc.), fire resistance and meteorological effects.

7.2. Ventilation concept

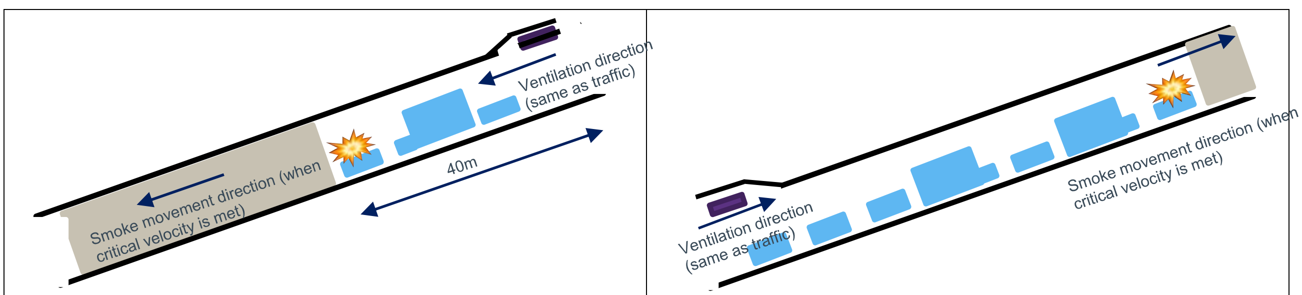
The conceptual ventilation system considered in the covered highway section has been selected to control smoke from a fire during emergency operation operating in conjunction with FFFS (see Section 5) and control pollution concentration levels (air quality) during normal and congested operation. IDA Tunnel software has been used to create a 1D model of the covered section to produce a longitudinal ventilation design that can meet both smoke and pollution control requirements. For more details on the modelling aspects refer to Appendix E.

7.2.1. Design Criteria

The concept ventilation system design smoke control requirements are based upon a fire with a convective heat release rate of 30MW, taken from the findings of the design fire analysis whereby the ventilation system is to operate in harmony with the FFFS (refer to technical note Partial Covered Lowered Lid Section – Design Fire Size and section 5 within this report). The ventilation system design takes into account parameters such as fire position, adverse wind and smoke buoyancy effects. Engineering analysis has been undertaken to determine the design fire scenario as described below:

The worst case fire location occurs in the westbound bore as the ventilation system has to move the smoke down a gradient against the natural buoyancy effect of the hot gases. In this situation the buoyancy effect has a greater impact on the achievable tunnel velocity than the resistance created by traffic stopped in the tunnel. Therefore the closer the fire to the entrance portal, the greater vertical distance the smoke has to be moved down and the lower the achievable velocity in the tunnel. If the fire is too close to the entrance portal then it is likely to destroy the jet fan bank, however in this situation it is considered acceptable for the smoke to naturally self-ventilate the small distance up the gradient and out of the entrance portal, where there will be very few vehicles trapped upstream of the fire. An engineering judgment has therefore been made that the worst case fire location in the westbound bore is 40m inside the cover from the entrance portal.

In the eastbound bore due to the positive gradient the natural buoyancy effect of the smoke will act in the direction of ventilation. It should be noted that, for conservatism, this beneficial effect is not taken into account when designing the ventilation system but there will nevertheless be an advantage over the westbound bore where buoyancy effects act against the direction of ventilation. Without a negative buoyancy effect the worst case fire location occurs at the end of the tunnel (east end) where the tunnel will be full of vehicles creating extra resistance to the airflow (see Figure 7-1 below).



Westbound ventilation concept	Eastbound ventilation concept

Figure 7-1 Ventilation Concept schematic concept for smoke control (eastbound/westbound)

7.2.2. Longitudinal Tunnel Ventilation System

7.2.2.1. Concept design

The proposed concept for the ventilation of the tunnel is a mechanical longitudinal ventilation system consisting of a single row of evenly-spaced jet fans located in a niche at the entrance of each portal. Jet fan performance details are presented in Table 7-1 and the jet fan location and number for each bound in Table 7-2 Jet fan locations.

The ventilation capacity required for smoke control is significantly greater than that for pollution control. The design capacity of the ventilation system is therefore sized for smoke control.

Table 7-1 Jet fan performance details

Parameter	Value
Rotor diameter	1220 mm
External diameter	1338 mm
Fan duty	1003 N
Jet velocity	32.9 m s^{-1}
Absorbed power	27.81 kW
Motor rating	36 kW
Full load current	67.8 A
Electrical supply	380-420 V, 50 Hz, 3-phase

Table 7-2 Jet fan locations

Westbound route		Eastbound route	
Fan row location	**Number of fans**	**Fan row location**	**Number of fans**
Niche at entry portal	13	Niche at entry portal	12

7.2.2.2. Westbound Bore Concept Design

The concept design for the westbound bore is for 13No 1.12m diameter jet fans, two of which are for meeting redundancy requirements. Initial jet fan selection has indicated that an outlet velocity of 32.9m/s is required for each fan. All fans are to be located in one bank housed in a fan niche just east of the Clayton Lane Bridge. The niche should be as close as possible to the East (entry portal) in order that the maximum possible fire locations can be effectively ventilated for. Figure 7-2 and Figure 7-3 give an indicative design for niche located jet fans, evenly spaced across the tunnel width. A niche of 5 feet in height has been assumed which allows for complete accommodation of the fans and supports.

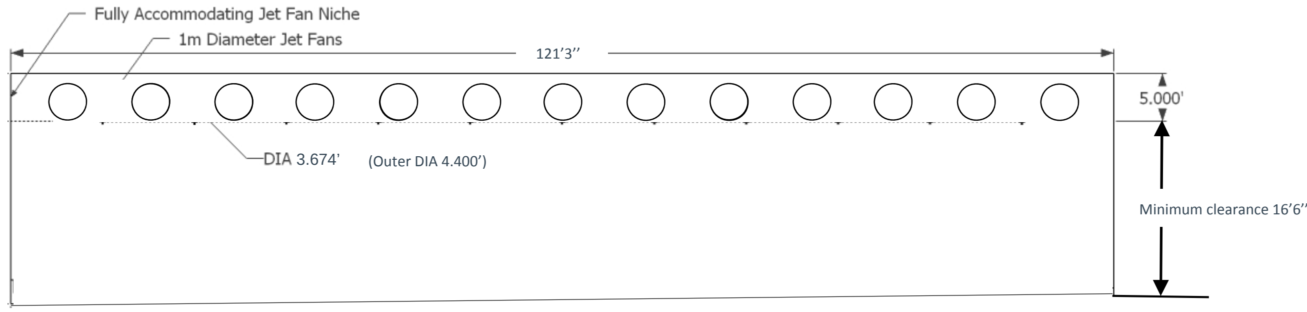


Figure 7-2 System concept design for westbound bore[7] (not to scale)

7.2.2.3. Eastbound Bore Concept Design

The cross-sectional area of the entrance portal of the eastbound bore is slightly smaller than the westbound bore and therefore there is less space for distribution of jet fans across the width. However the design criteria for the eastbound bore is less demanding. In order to meet the critical velocity for a fire at the worst case location 12No 1.12m diameter jet fans of the same specification as the westbound bore ventilation system are required, two of which are to meet fan redundancy requirements. It is assumed that these fans will be distributed evenly across the tunnel width and housed in a full accommodating fan niche situated just west of the Columbine Street bridge as shown in Figure 7-3.

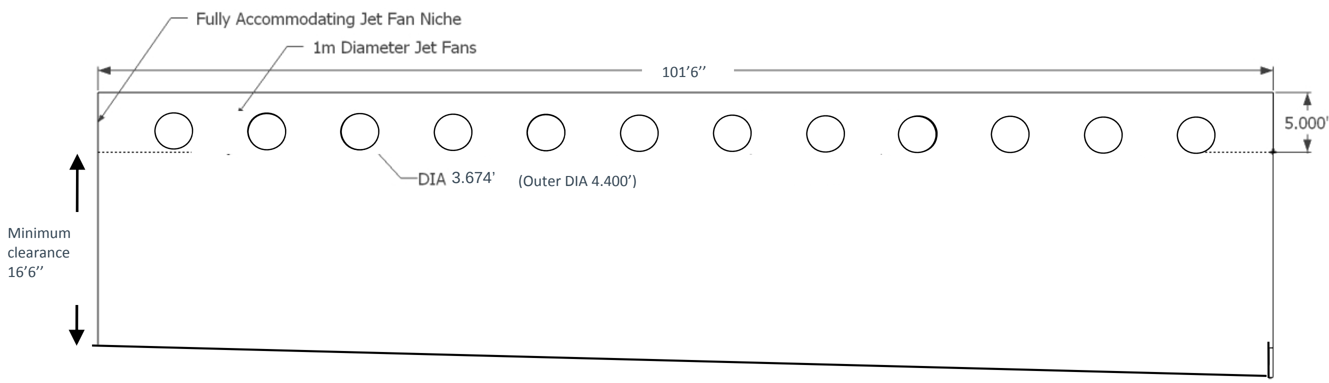


Figure 7-3 System concept design for eastbound bore (not to scale)

Table 7-3 Fan Redundancy

Fan operational security must be maintained at all times. The system is designed to operate to its design requirement even when a fan is unavailable either due to routine maintenance or occasional failure. NFPA 502 indicates that ventilations systems that can be directly exposed to a fire shall consider fan redundancy, but no further guidance on the number of redundant jet fans to be accounted for is provided. The current UK

[7] Minimum clearance and headroom for jet fan positioning in Figure 7-2 and Figure 7-3 taken from ANA CAD drawing 13599DES_Model01_UPRR_Section 2.dgn. Width at each portal end taken from ANA hand sketched sections titled SKM_C364e15011307500.pdf

standard used in the design of road tunnels BD78/99 specifies that it is necessary to provide a level of standby fans in order to give an acceptable level of redundancy. For normal operation, design requirements should be met with 2 fans out of service. For emergency operation design requirements should be met when fans close to the fire are assumed destroyed in addition to redundancy for normal operation. As stated earlier, for this project, it is considered acceptable for smoke from a fire that is in close enough proximity to the jet fan bank to destroy it, to ventilate naturally. The emergency case redundancy requirement is therefore not necessary. The ventilation design therefore includes 2No. standby jet fans for redundancy in addition to those required for smoke control design requirements.

7.2.2.4. Recirculation

Recirculation of pollution or smoke from the exit of one bore into the entrance of the other needs to be avoided. Unless designed for, this will be a significant problem due to the depressed nature of the highway where air may have the tendency to get trapped. A dividing wall between the two traffic directions should be built extending from both portals of the covered section. Guidance from BD78/99 [21] suggests the wall could be up to 40m in length. Figure 7-4 gives a copy of a typical dividing wall design taken from BD78/99.

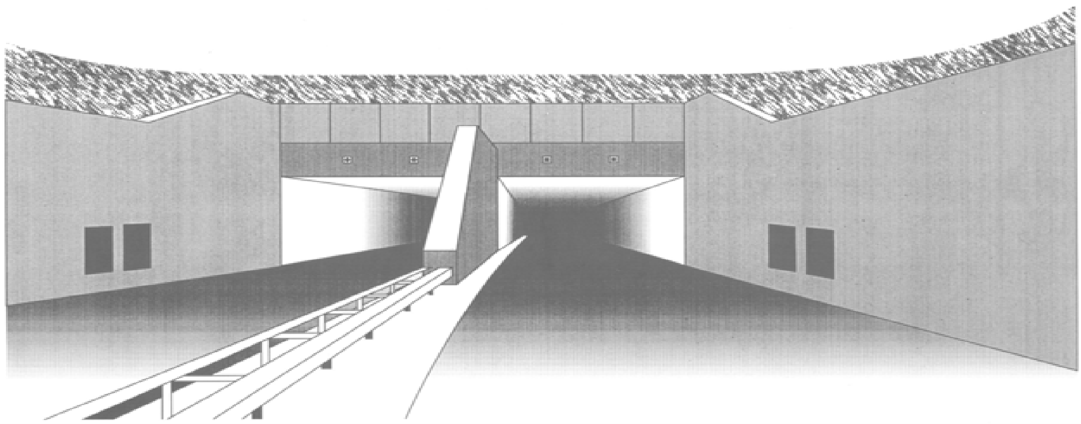


Figure 7-4 Example of recirculation dividing wall from BD78/99 [17]

7.2.2.5. Noise

Care should be taken when selecting fans that noise levels in the tunnel particularly during emergency operations are not so high as to interfere with the use of emergency communication systems. Annex B of NFPA 502 [1] gives guidance on noise levels for maintain a tenable environment for emergency escape. It suggests that noise levels should be a maximum of 115dBA for a few seconds and a maximum of 92dBA for the remainder of the exposure, a measurement plane is not specified by this standard. The UK standard BD78/99 specifies that fan noise levels in the tunnel, particularly at times of emergency use, should be not so high as to interfere with the use of emergency communication systems. The NR85 noise spectrum should not be exceeded at a measurement plane 1.5 m above the road surface, this value is more onerous when compared with NFPA 502 guidance values (when assuming the same measurement plane as suggested by BD78/99 standard).

Jet fan noise is minimised through the use of silencers (two diameters in length) and acoustic pods. Additionally, an appropriate balance between fan speed, diameter, blade angle, jet velocity and thrust are considered during the fan selection process to achieve the required performance within the noise criteria suggested in NFPA502.

The sound spectrum for the chosen jet fan model is presented in Table 7-4. An acoustic analysis by Atkins [42] indicates that the suggested NR85 noise limit (most onerous case) will not be exceeded at a plane 1.5 m above the road surface for a fan selection of 11 fans (see Table 7-4 below). An additional case with 24 jet fans with the same sound spectrum specifications has been included for comparative purposes.

Table 7-4 Sound spectrum for a single jet fan

	Sound frequency [Hz]								Overall sound power level [dB]	
	63	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	L_W [dB]	L_{WA} [dB (A)]
L_W	88	88	92	82	80	83	82	77	96	90

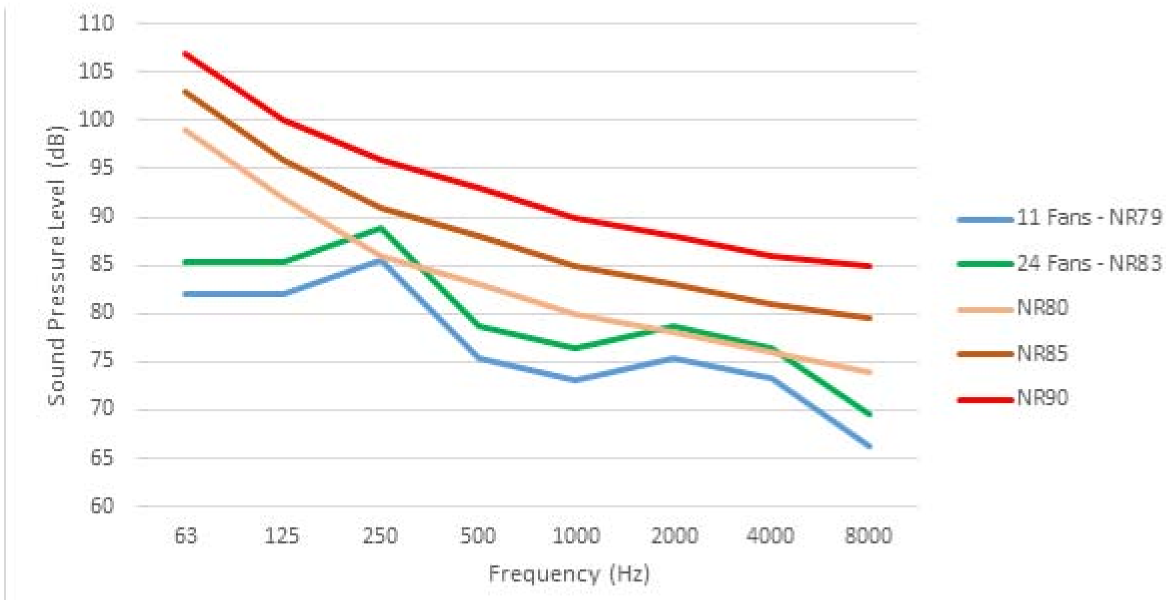


Figure 7-5 Acoustic analysis Preliminary Results

The figure above shows the noise levels predicted for the position directly under the fans at 3m from the tunnel opening for two scenarios (11 and 24 fans). Based on these results the predicted noise levels fall under NR85 at 1.5m from the road surface. However these results are approximate, but are likely to be within 3dB. Further and more detailed analysis is out of the scope this report.

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Appendices

Appendix A. NFPA 502 requirements

A.1. Road Tunnel Fire protection requirements

Table A.7.2 Minimum Road Tunnel Fire Protection Reference Guide

Fire Protection Systems	NFPA 502 Sections	Road Tunnel Categories X *[See 7.2(1).]*	A *[See 7.2(2).]*	B *[See 7.2(3).]*	C *[See 7.2(4).]*	D *[See 7.2(5).]*
Engineering Analysis						
Engineering analysis	4.3.1	MR	MR	MR	MR	MR
Fire Protection of Structural Elements[a]						
Fire protection of structural elements	7.3	MR	MR	MR	MR	MR
Fire Detection						
Detection, identification, and location of fire in tunnel	7.4	—	—	MR	MR	MR
Manual fire alarm boxes	7.4.6	—	—	MR	MR	MR
CCTV systems[b]	7.4.3	—	—	CMR	CMR	CMR
Automatic fire detection systems[b]	7.4.7	—	—	CMR	CMR	CMR
Fire alarm control panel	7.4.8	—	—	MR	MR	MR
Emergency Communications Systems[c]						
Emergency communications systems	4.5/7.5	CMR	CMR	CMR	CMR	CMR

Table A.7.2 *Continued*

Fire Protection Systems	NFPA 502 Sections	Road Tunnel Categories X *[See 7.2(1).]*	A *[See 7.2(2).]*	B *[See 7.2(3).]*	C *[See 7.2(4).]*	D *[See 7.2(5).]*
Traffic Control						
Stop traffic approaching tunnel portal	7.6.1	MR	MR	MR	MR	MR
Stop traffic from entering tunnel's direct approaches	7.6.2	—	—	MR	MR	MR
Fire Protection						
Fire apparatus[d]	7.7	—	—	—	—	—
Fire standpipe	7.8/10.1	—	MR	MR	MR	MR
Water supply	7.8/10.2	—	MR	MR	MR	MR
Fire department connections	10.3	—	MR	MR	MR	MR
Hose connections	10.4	—	MR	MR	MR	MR
Fire pumps[e]	10.5	—	CMR	CMR	CMR	CMR
Portable fire extinguishers	7.9	—	—	MR	MR	MR
Fixed water-based fire-fighting systems[f]	7.10/9.0	—	—	—	CMR	CMR
Emergency ventilation system[g]	7.11/11.0	—	—	CMR	CMR	MR
Tunnel drainage system[h]	7.12	—	CMR	MR	MR	MR
Hydrocarbon detection[h]	7.12.7	—	CMR	MR	MR	MR
Flammable and combustible environmental hazards[i]	7.15	—	—	CMR	CMR	CMR
Means of Egress						
Emergency egress	7.16.1.1	—	—	MR	MR	MR
Exit identification	7.16.1.2	—	—	MR	MR	MR
Tenable environment	7.16.2	—	—	MR	MR	MR
Walking surface	7.16.4	—	—	MR	MR	MR
Emergency exit doors	7.16.5	—	—	MR	MR	MR
Emergency exits (includes cross-passageways)[j]	7.16.6	—	—	MR	MR	MR
Electrical Systems[k]						
General	12.1	—	CMR	MR	MR	MR
Emergency power	12.4	—	CMR	MR	MR	MR
Emergency lighting	12.6	—	CMR	MR	MR	MR
Exit signs	12.6.8	—	CMR	MR	MR	MR
Security plan	12.7	—	CMR	MR	MR	MR
Emergency Response Plan						
Emergency response plan	13.3	MR	MR	MR	MR	MR

MR: Mandatory requirement (3.3.37). CMR: Conditionally mandatory requirement (3.3.37.1).
Note: The purpose of Table A.7.2 is to provide guidance in locating minimum road tunnel fire protection requirements contained within this standard. If there is any conflict between the requirements defined in the standard text and this table, the standard text must always govern.
[a]Determination of requirements in accordance with Section 7.3.
[b]Determination of requirements in accordance with Section 7.4.
[c]Determination of requirements in accordance with Sections 4.5 and 7.5.
[d]Not mandatory to be at tunnel; however, they must be near to minimize response time.
[e]If required, must follow Section 10.5.
[f]If installed, must follow Section 7.10 and Chapter 9.
[g]Section 11.1 allows engineering analysis to determine requirements.
[h]If required, must follow Section 7.12.
[i]Determination of requirements in accordance with 7.16.2.
[j]Emergency exit spacing must be supported by an egress analysis in accordance with 7.16.6.
[k]If required, must follow Chapter 12.

A.7.3.2 Any passive fire protection material should satisfy the following performance criteria:

(1) Be resistant to freezing and thawing
(2) Withstand dynamic suction and pressure loads
(3) Withstand both hot and cold thermal shock from fire exposure and hose streams
(4) Meet all applicable health and safety standards
(5) Not itself become a hazard during a fire
(6) Be resistant to water ingress

The time-temperature development is shown in Table A.7.3.2(a) and in Figure A.7.3.2(a).

An engineering analysis for the purposes of determining the appropriate time-temperature curve should consider the following:

(1) Tunnel geometry
(2) Types of vehicles anticipated
(3) Types of cargoes
(4) Any additional fire mitigation measures
(5) Expected traffic conditions

Figure 8-1 Figure NFPA 502 Road Tunnel Fire Protection

From Figure 8-1 above it can be seen that amongst the mandatory requirements for the cover classified as category C are: means of identifying fire location, fire alarm control panels, communication systems, fire protection systems (excluding fire pumps, emergency ventilation, which are conditionally mandatory and fire apparatus which is not mandatory). Means of egress and electrical systems are also mandatory for a category C tunnel. Requirements in section 4 to are taken from NFPA 502 unless a specific reference is given.

It is to highlight that this current NFPA 502 edition (2014) has introduced new requirements and also modified some of its requirements in specific for a category C tunnel. Amongst the new mandatory requirements for a category C tunnel are engineering analysis, protection of structural elements and within means of egress walking surface and emergency exits (including cross passageways) and exit doors. The introduced conditionally mandatory elements are: Emergency communications systems (previously mandatory), fixed fire suppression, flammable and combustible environmental hazards analysis.

Appendix B. Fire Frequency Analysis

B.1. Introduction

An assessment has been made of the likely return periods for fires of different severities. This is done using a statistical approach with tunnel and traffic data; and expected fire rates.

For the fire frequency analysis the two bores carrying each traffic direction are considered as independent tunnels. The vehicle mix distribution is assumed equal in both traffic directions however predictions for 2035 [9] give an 6% higher traffic volume for the westbound bore making it the worst case scenario. Analysis has therefore been performed on the westbound bore only as it is considered representative of both traffic directions.

B.2. Input data

B.2.1. Vehicle Traffic

CDOT traffic data have been provided by ANA. The study uses projected traffic volume data for the I70 for year 2035 which includes AADT figures for eastbound and westbound separately. Data is given for two lane configuration alternatives for which the fire frequency analysis uses general purpose + Managed lane option. The study assumes that that the percentage of trucks is equal in both traffic directions. Data has also been provided by CDOT giving the vehicle type distribution [10] for the I70 covered section. The proportion of dangerous goods vehicles is not given in this data.

For dangerous goods –HazMat- (i.e. fuel tankers) it is assumed there are no restrictions of such vehicle on the I70 given the route is an interstate highway. For the percentage of dangerous goods, in absent of any specific I70 data, it has been assumed that the percentage of dangerous goods vehicles is similar to the Europe United States road network as referred on [34] as the percentage of the total number of trucks carrying HazMat, this percentage is 7%.

Table 8-1I70 Covered Highway Traffic

	Value	Reference
AADT 2035 westbound PCL ML - full built- (vehicles/day)	115,964	ANA (Table titled All Day Traffic Volumes and Congested Speeds for the PCL ML (Full Build) I-70 Alternative January 27, 2015) [9]
Covered section length (ft, [m])	999 [304]	[14]
Vehicle miles per year [veh-km/year]	8,008,434 [12,888,325]	Calculated as AADT x Length x 365
%Trucks –HGVs	3.3	[10
%Buses	2.3	[10]
%Dangerous Goods (HazMat)	0.2	Calculated as 7%x(%trucks) from [34]
%Cars	94.5	[10]

For HGVs without dangerous goods, the DARTS analysis method divides vehicles into flammable and non-flammable (or empty) loads. According to a National Private Truck Council (NPTC) research in the US 28%

of all miles private fleet trucks ran empty in the year 2009, therefore the assumption is made that 28% of all trucks run empty.

B.2.2. Fire rates

The expected fire rates [fire per veh mile; (fire per veh km)] are derived from NFPA and FHWA statistical data for travelled distance ([22],[23],[17]) for cars, buses and HGVs and for Dangerous Goods reference[23] and summarised in Table 8-2 below.

Table 8-2 U.S. Estimate Fire rates by vehicle category

	Value	Reference
Highway Vehicle fires (year 2013)	164,000	[22] NFPA document Appendix table, Fire Loss in the United States Trend Tables. Table titled U.S. Highway Vehicle Fire Problem
%passenger car fires (average years 2008-2010)	91.12	[23] FEMA Topical Fire report Series Table 2. Types of Highway Vehicle Fires (2008–2010)
%bus fires (average years 2008-2010)	0.70	As above
%HGV fires (average years 2008-2010)	7.28	As above
Passenger road vehicles fires estimated for year 2013 [fires/year]	149,435	Calculated (164000x91.12%)
Bus fires [fires/year]	1148	Calculated (164000x0.7%)
Truck fires [fires/year]	11,941	Calculated (164000x7.28%)
Passenger road vehicle Travelled distance [mill miles/year] (mill km /year)	2,677,771 (4,309,454)	FHWA tables for year 2013 Annual Vehicle Distance Travelled in miles and related data by highway category and vehicle type. [17]
Buses Travelled distance [mill miles / year] (mill km /year)	15,167 (24,408)	As above
Trucks Travelled distance [mill miles / year] (mill km /year)	275,018 (442,598)	As above
Passenger road Fire rate [fire per Veh-mile] (fire per Veh-km)	[5.58E-08] (3.47E-08)	Calculated as ([fires /year] / travelled distance for the specific vehicle type
Buses Fire rate [fire per Veh-mile] (fire per Veh-km)	[7.57E-08] (4.70E-08)	As above
Trucks Fire rate ([fire per Veh-mile] (fire per Veh-km)	[4.34E-08] (2.70E-08)	As above
Dangerous Goods (HazMat) [fire per Veh-mile] (fire per Veh-km)	1.64E-9 (1.02E-9)	[18]

B.2.3. Traffic Mode

Traffic is proposed to be unidirectional. Contraflow (bi-directional traffic in a single bore) has been assumed to be not required in the I70 tunnel given the available alternative routes during night time maintenance closures.

B.2.4. Fire Severity

Fires in the tunnel for each vehicle class are subdivided into small, moderate or large (serious) fires; categorised in terms of the peak heat release rate.

DARTS data indicate that there is an 80% likelihood that fire will be limited to a small size with 20% reaching a moderate to large size. Of the 20% that reach a moderate to large size, a proportion of those will be more serious. As DARTS data are based on a range of vehicle fires, mainly in Europe, and given the lack of available data for U.S. tunnel fires there is a degree of uncertainty in these figures. Given the uncertainty of these numbers as they relate to U.S. tunnels, sensitivity analysis has been undertaken.

DARTS data on 'serious' fires indicate a range of estimated peak heat release rates from 15MW upwards, with serious consequences in terms of damage, disruption and personal injury. Serious fires are thus assumed to involve a fire load releasing heat at a rate of at least 15MW. DARTS concludes that 1% of all fires can be characterised as serious. DARTS data also show that 15% of serious fires originate in PVs (cars and campers included) and 85% in HGVs (trucks) and buses. The probability for all HGV fires to develop in a serious fire rates is 2.5% (1%*85%/33%[8]) and for car fires 0.23% (1%15%/67%) is calculated by DARTS.

According to DARTS, 10% of 'serious' fires go out of control (90% are controlled), this value is input to the event tree. Out of control fires are defined as those that reach a more extreme heat release rate for their category, guidance for the different vehicle classes are presented in the DARTS work and these are taken to inform the development of the scenario output fire size categories for this work. There is a degree of judgement and subjectivity in this categorisation but the process provides a means to represent the full range of fire risk scenarios for the tunnel. The sensitivity of the results to the judgements made is assessed as part of the sensitivity analysis.

With regards Dangerous Goods (HazMat), the United States Nuclear Regulatory Commission (U.S.NRC) has recently undertaken analysis on roadway accidents involving long duration fires [18]. Their analysis is based upon twelve years of HazMat accidents registered (1997-2008) and has identified all fires and those within the 'severe' category. Their definition of a 'severe' fire complies with the following: persistent fire for an extended period of time, more than one vehicle involved, fuel was flammable liquid that could pool under another vehicle. For the purposes of this study we have taken a severe fire to fall within the NRC serious fires for liquid cargo. 23 fires out of 477 were considered severe fires, therefore the probability of serious fires is:

- A probability of 4.82% serious HazMat liquid.

From the same study it is also known that 8% of the fires involved flammable gas, whereas the rest were flammable liquid (69%), oxidiser (5%), radioactive (1%). These have been grouped on the event tree as liquid and others and gaseous flammable fires.

For gaseous flammable fires, in the absence of data DARTS assumptions have been taken for distribution of jet fires (30%), flash fires (40%) and BLEVEs (30%).

B.2.5. Fire Frequency

For the event tree, the number of fires per year in each fire size category is the product of:

- The total traffic in the tunnel [vehicle-km/year];
- The fraction of vehicles per vehicle class [%vehicles of each class];
- The traffic mode proportion [% flow in each traffic mode];

[8] 33% and 67% are the Proportion of fires caused by HGVs & passenger cars respectively estimated by DARTS [3]

- The expected fire rate in the tunnel [fire /veh-km];
- The proportion of fires developing to different fire sizes [%] and for the serious fires;
- The proportion of out of control fires [%].

The fire return period [years] is the inverse of the calculated fire frequency.

B.3. Results

The assessed fire return periods are shown in Table 8-3 below. These data have been grouped in ranges of 5MW fires (17MBtu/h), 15MW (51MBtu/h), 30MW (102MBtu/h), 150MW (512MBtu/h), 300MW (1,024MBtu/h).

Table 8-3 Estimated fire return periods

Vehicle Type	Traffic Type	Fire Severity	Fire Size (MW) [MBtu/h]	Fire Return Period (years)
Car	Normal	Small	5 [17]	3
		Moderate	15 [51]	12
		Large – In control	15 [51]	1,144
		Large – Out of control	30 [102]	10,295
		Large – Out of control	150 [512]	10,295
Bus	Normal	Small	5 [17]	90
		Moderate	15 [51]	410
		Large – In control	30 [102]	3,188
		Large – Out of control	150 [512]	28,691
Un-laden HGV	Normal	Small	15 [51]	401
		Moderate	30 [102]	1,834
		Large – In control	150 [512]	14,266
		Large – Out of control	300 [1,024]	128,391
Laden HGV	Normal	Small	15 [51]	156
		Moderate	30 [102]	713
		Large – In control	150 [512]	713
		Large – Out of control	150 [512]	5,548
		Large – Out of control	300 [1,024]	49,930
	Liquid	Small	30 [102]	35,887
		Moderate	150 [512]	164,053

Vehicle Type	**Traffic Type**	**Fire Severity**	**Fire Size (MW) [MBtu/h]**	**Fire Return Period (years)**
Dangerous Goods Vehicles		Large – In control	150 [512]	1,275,970
		Large – Out of control	300 [1,024]	11,483,731
	Gas	Jet	300 [1,024]	1,100,524
		Flash	300 [1,024]	825,393
		BLEVE	300 [1,024]	1,100,524

Appendix C. MOVES Input Information

C.1. Navigation Panel Inputs

The following inputs provide a general description of the model and are all input to the Navigation Panel of the MOVES software.

- A ‘Project’ scale model is used in order to model the covered section as an individual link.
- Denver County within Colorado is used as the Geographic bound. The covered section of the I70 falls within this county and the use of which provides significant county specific default data not available if a Custom Domain is created. The default average barometric pressure for this county is 24.087inHg which is considered adequately close to the barometric pressure for the project specific elevation.
- The month of January is specified as the design month as this was the month of data provided by CDOT and tends to be coldest month for the county. A design hour of 08:00-09:00 is specified as the temperatures at this peak period are lower than in the afternoon peak period.
- For simplicity and conservatism purposes only gasoline and diesel fuels are included in the model.
- The road type is specified as Urban Restricted Access. Restricted access refers to the road only being accessible at predetermined locations such as at on-ramps.
- No on-road retrofit or rate of progress strategies are implemented in the model.

C.2. Project Scale Specific Inputs

The following points summarise the detailed data sets that are used as inputs to the model. Any assumptions made are explained here.

- Fuel supply and formulation data is taken directly from default data.
- Meteorological data supplied by ANA [31] for the Denver County in January between 08:00 and 09:00 AM. This uses a temperature of 15.8℉ and a relative humidity of 58.1%.
- Default Inspection and Maintenance Programs are used for Colorado State and Denver County.
- Vehicle age distributions were provided by CDOT [31].
- Default fuel type and engine technology data are used.

C.2.1. Link Definition

The link length is defined as 0.189205 miles (999ft) with an average gradient of 1.146% and is therefore modelling the eastbound bore where the uphill gradient is the worst case. The worst case traffic assumption is that all 6 lanes (3 GP lanes, 2 ML lanes and 1 Ramp-off) are at peak capacity.

The link traffic definition data are redefined for each simulation for the range of average vehicle speeds. The vehicle volume is determined by interpolation of the road capacity traffic defined by PIARC 2012 [16], shown in Table C-1, the results of which can be found in the link definition Table C-2.

Table C-1 PIARC average peak traffic densities for an urban uni-directional tunnel

		Traffic Density/lane	
Traffic Description	**Traffic Speed (km/h)**	**Passenger car units per km (pcu/km)**	**Passenger car units per hour (pcu/h)**
Fluid traffic	60	33	2000
Congested traffic	10	100	1000
Standstill	0	165	-

For converting passenger car units into number of vehicles, a truck/bus may be assumed to occupy the space of 2 passenger cars in free flowing traffic and up to 3 passenger cars in slow moving traffic.

Table C-2 Link traffic volume and speeds

Link Average Speed (mph)	Truck/Bus pcu Definition	Lane Traffic Volume (veh/h/lane)	Link Traffic Volume (veh/h)
0	3	45*	271*
2.5	3	362	2169
5	3	724	4344
10	3	1342	8050
20	2	1751	10504
30	2	1931	11586

*At 0mph Lane and Link traffic volume is a total for the given road length

C.2.2. Link Source Types

The Link Source Types defines the vehicle type split on the modelled stretch of road. CDOT provided [31] link source distribution which is given below in Table C-3.

Table C-3 Vehicle type proportions

Vehicle Type	Proportion
Motorcycle	3.45%
Passenger car	48.75%
Passenger truck	31.93%
Light commercial truck	10.29%
Intercity bus	0.39%
Transit bus	0.26%

School bus	1.68%
Refuse truck	0.04%
Single unit short haul truck	1.60%
Single unit Long haul truck	0.10%
Motor home	0.16%
Combination short haul truck	0.77%
Combination long haul truck	0.59%

C.2.3. Vehicle Operating Modes

No link drive schedule or operating mode distribution has been specified and therefore MOVES uses the average speed specified and road type to automatically define vehicle operating modes. Where the average vehicle speed is lower than the default data range the nearest speed is used (no extrapolation occurs, only interpolation). This is considered a reasonable approximation for this level of modelling however more appropriate vehicle operating modes for congested traffic could be specified manually if the required data are available. For standstill traffic where the specified average link speed is 0mph, the software applies extended idle operating modes to all vehicle types.

Appendix D. Portal Emissions Input Data

D.1. Traffic Conditions

Predicted traffic conditions for 2035 [32], given here in Table D-1 have been used in order to run a MOVES model to calculate vehicle emissions generated in the covered section during normal operation.

Table D-1 2035 Traffic volumes and speed for PCL ML Full Build traffic

		LID 1 - PCL ML (Full Build)											
		General Purpose + Managed Lane Option											
		WB GP (9220)		WB ML (43308)		WB Steele On (43257)		EB GP (43360)		EB ML (43305)		EB Steele Off (43269)	
From	To	Hourly Volume	Period Speed (mph)*	Hourly Volume	Period Speed (mph)	Hourly Volume	Period Speed (mph)	Hourly Volume	Period Speed (mph)	Hourly Volume	Period Speed (mph)*	Hourly Volume	Period Speed (mph)
12:00 AM	1:00 AM	318	64.0	0	64.0	11	39.0	285	64.0	0	64.0	39	39.0
1:00 AM	2:00 AM	127	64.0	0	64.0	4	39.0	114	64.0	0	64.0	15	39.0
2:00 AM	3:00 AM	127	64.0	0	64.0	4	39.0	114	64.0	0	64.0	15	39.0
3:00 AM	4:00 AM	191	64.0	0	64.0	7	39.0	171	64.0	0	64.0	23	39.0
4:00 AM	5:00 AM	508	64.0	0	64.0	18	39.0	456	64.0	0	64.0	62	39.0
5:00 AM	6:00 AM	2,033	63.9	0	64.0	71	39.0	1,823	64.0	0	64.0	247	38.9
6:00 AM	7:00 AM	5,310	32.7	829	47.8	649	34.2	4,269	59.0	792	60.0	1,039	22.0
7:00 AM	8:00 AM	6,881	17.0	1,879	31.2	1,412	26.7	5,227	46.8	1,760	51.3	1,767	16.1
8:00 AM	9:00 AM	6,066	32.7	1,897	47.8	1,048	34.2	4,335	59.0	1,664	60.0	1,532	22.0
9:00 AM	10:00 AM	4,772	56.1	594	64.0	460	38.8	3,711	62.6	1,237	62.6	712	37.4
10:00 AM	11:00 AM	4,540	56.1	565	64.0	437	38.8	3,530	62.6	1,177	62.6	677	37.4
11:00 AM	12:00 PM	5,074	47.9	782	63.6	589	38.2	3,812	61.4	1,568	61.4	824	35.6
12:00 PM	1:00 PM	5,491	39.7	984	63.2	731	37.6	4,003	60.2	1,929	60.2	952	33.8
1:00 PM	2:00 PM	5,295	39.7	949	63.2	704	37.6	3,860	60.2	1,860	60.2	918	33.8
2:00 PM	3:00 PM	6,079	39.7	1,090	63.2	809	37.6	4,431	60.2	2,135	60.2	1,054	33.8
3:00 PM	4:00 PM	5,258	30.6	1,448	48.0	1,202	28.0	4,735	44.4	1,800	44.4	1,128	27.1
4:00 PM	5:00 PM	6,426	30.6	1,770	48.0	1,469	28.0	5,787	44.4	2,201	44.4	1,379	27.1
5:00 PM	6:00 PM	6,131	23.0	1,782	42.2	1,585	22.3	5,662	35.0	1,971	35.2	1,395	23.0
6:00 PM	7:00 PM	5,264	43.3	1,628	56.2	1,202	31.3	4,876	51.9	1,751	54.7	1,112	30.7
7:00 PM	8:00 PM	4,060	63.9	0	64.0	144	39.0	3,724	64.0	0	64.0	514	38.9
8:00 PM	9:00 PM	2,394	63.9	0	64.0	85	39.0	2,196	64.0	0	64.0	303	38.9
9:00 PM	10:00 PM	2,186	63.9	0	64.0	77	39.0	2,005	64.0	0	64.0	277	38.9
10:00 PM	11:00 PM	1,770	63.9	0	64.0	63	39.0	1,623	64.0	0	64.0	224	38.9
11:00 PM	12:00 AM	635	64.0	0	64.0	22	39.0	570	64.0	0	64.0	77	39.0
Total		86,934		16,197		12,803		71,319		21,845		16,286	
		115,934						109,450					

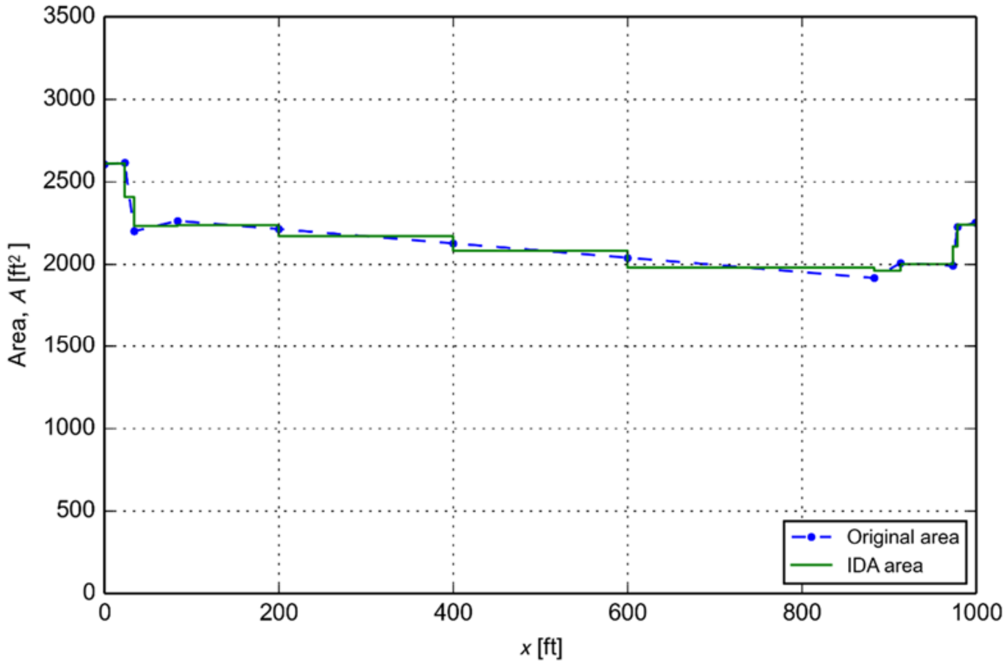
Appendix E. Ventilation modelling for emergency scenario

E.1. General Modelling Assumptions

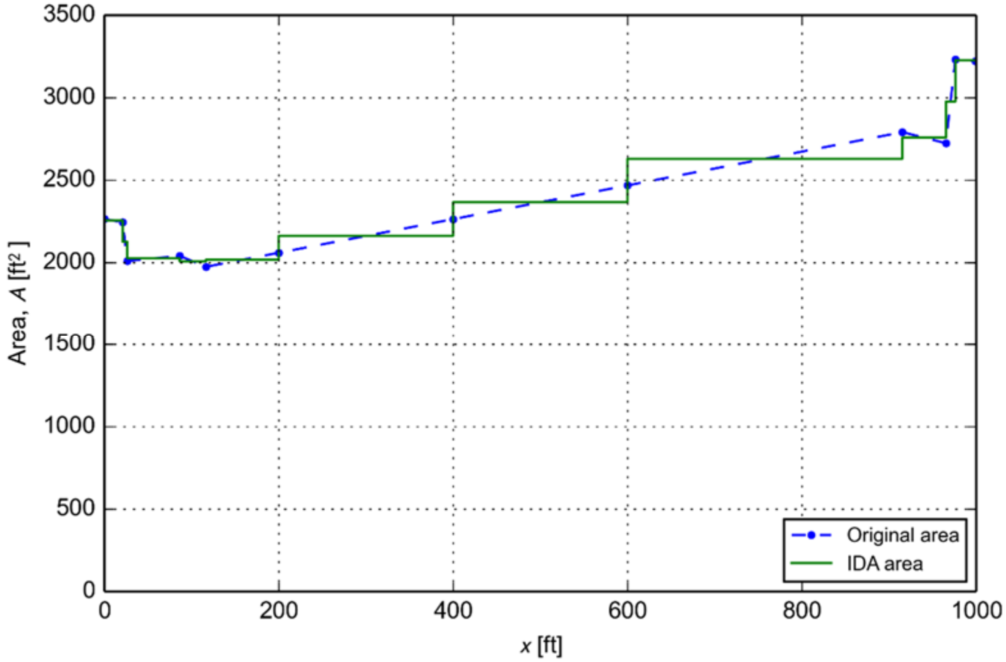
E.1.1. Tunnel Geometry

The air flow rate through the tunnel, whether induced by vehicles or the ventilation system, is influenced by tunnel cross sectional area, length and hydraulic diameter.

The westbound and eastbound routes feature gradual changes in width over their lengths and niches at each portal. The resulting distribution of cross-sectional area with length is simplified in the one-dimensional flow model in IDA Tunnel, as shown in Figure 8-2.



(a) Westbound route



(b) Eastbound route

Figure 8-2 Simplification of tunnel geometry in one-dimensional flow model

The segmented geometry is tabulated Table 8-2 and Table 8-3 . The uphill gradient (~1%) in the eastbound bore is expected to result in greater emissions generation. The downhill gradient in the southbound bore will increase the tendency of buoyant smoke and hot gases from a fire to travel uproad, increasing the jet fan thrust requirement.

Table 8-2 Westbound route geometry

Chainage [m]	Elevation[9] [m]	Area [m^2]	Gradient [%]	Height [m]
0	3.55	242.46	-0.9	6.51
7.03	3.49	223.59	-0.9	6.57
10.38	3.46	207.23	-0.9	5.49
25.57	3.32	207.84	-1.2	5.73
60.96	2.9	201.49	-1.2	5.74
121.92	2.18	193.43	-1.2	5.77
182.88	1.45	183.66	-1.2	5.79
269.1	0.43	182.16	-1.2	5.82

[9] For Vertical clearance and elevation drawing: 13599DES_Prof01_UPRR_Section 2.dgn. Confirmation received through email titled: Clarification of I70 Cover dimensions from Daniel Liddle to Conor Fleming, cc. Simon Drake, Yenny Gomez. 02nd February 2015 23:47 (GMT)

Chainage [m]	Elevation[9] [m]	Area [m²]	Gradient [%]	Height [m]
278.25	0.32	185.63	-1.2	6.11
296.53	0.1	195.78	-1.2	6.04
298.16	0.08	207.89	-1.2	6.78
304.5	0	207.89	-1.2	6.86

Table 8-3 Eastbound route geometry

Chainage [m]	Elevation [m]	Area [m²]	Gradient [%]	Height [m]
0	0	209.33	1.2	6.86
6.34	0.08	197.48	1.2	6.78
7.97	0.1	188.02	1.2	6.04
26.26	0.32	186.4	1.2	6.11
35.4	0.43	187.28	1.2	5.82
60.96	0.73	200.72	1.2	5.81
121.92	1.46	219.7	1.2	5.79
182.88	2.18	244.21	1.2	5.77
278.94	3.32	256.11	0.9	5.73
294.13	3.46	276.59	0.9	5.49
297.48	3.49	299.74	0.9	6.57
304.5	3.55	299.74	0.9	6.51

E.1.2. Hydraulic Losses

Minor Losses

Air flow through the covered section will be resisted by the aerodynamic drag of the tunnel lining (wall friction), including obstacles such as lights, signs and cables. Additional energy losses occur at the entrance and exit portals. The total tunnel resistance is expressed as a pressure drop,

$$\Delta p_{\mathrm{tunnel}} = \left(K_{\mathrm{entry}} + K_{\mathrm{exit}} + \lambda \sum_i \frac{L_i}{D_{h\,i}} \right) \frac{1}{2} \rho u^2 \tag{1}$$

where K_{entry} and K_{exit} represent the minor losses at the entry and exit, λ is the wall friction coefficient, ρ is density and u is velocity. The length L and hydraulic diameter D_{h} for each tunnel segment i are summed for the whole tunnel. The minor loss and wall friction coefficients are listed in Table 8-4. The values of the minor loss coefficients are widely accepted (see for example [37]). Although PIARC [19] recommend a value of $\lambda = 0.015$, a higher value of 0.02 is used here to reflect the conservatism required at this early stage of the project.

Table 8-4 Values of tunnel resistance coefficients

Coefficient	Value
K_{entry}	0.5
K_{exit}	1
λ	0.02

Adverse Wind Pressure

The effective resistance of the tunnel may increase due to meteorological conditions. Wind acting against the flow of traffic would elevate the local static pressure as it encounters the tunnel exit portal.

A wind rose representing wind direction and velocity at Denver International Airport in the period from January 1995 to December 2014 is presented in Figure 8-3 with data provided by the National Climatic Data Center website [29].

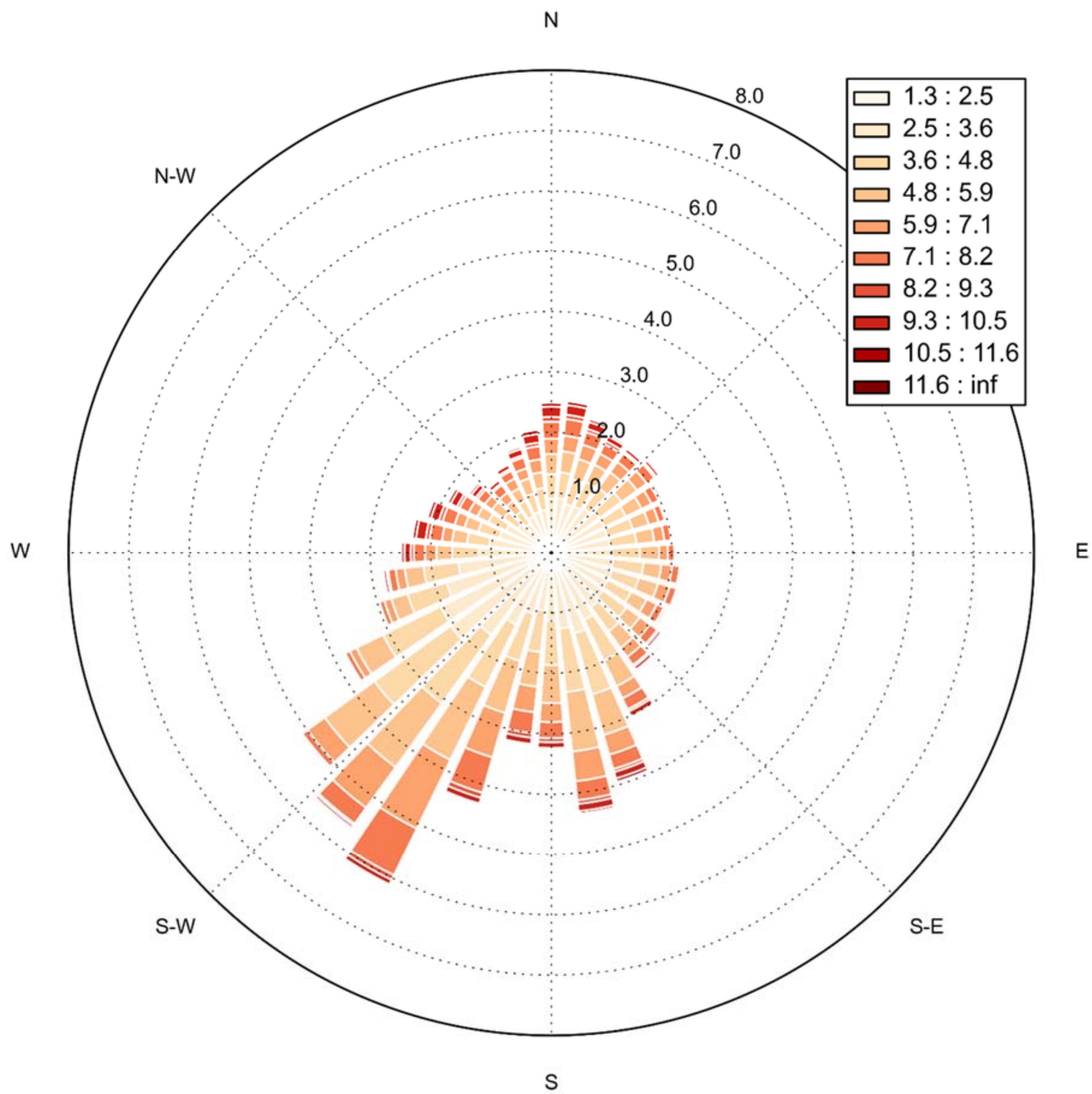


Figure 8-3 Wind rose indicating prevailing wind direction and velocity (m/s) at Denver International Airport between 1995 and 2014.

The east-aligned and west-aligned components of this wind rose are resolved as

$$V_{\mathrm{east}} = V \sin\theta \,|_{\theta<\pi}$$
$$V_{\mathrm{west}} = -V \sin\theta \,|_{\theta\geq\pi} \qquad (2)$$

where V is wind velocity in m s^{-1} and θ is the wind direction relative to North, increasing in the clockwise direction. The resulting east and west wind speed frequency distributions are presented in Figure 8-4. The portal pressure is calculated based on the 95th percentile velocities of 6.15 m s^{-1} (east) and 6.72 m s^{-1} (west), indicated by the broken red lines.

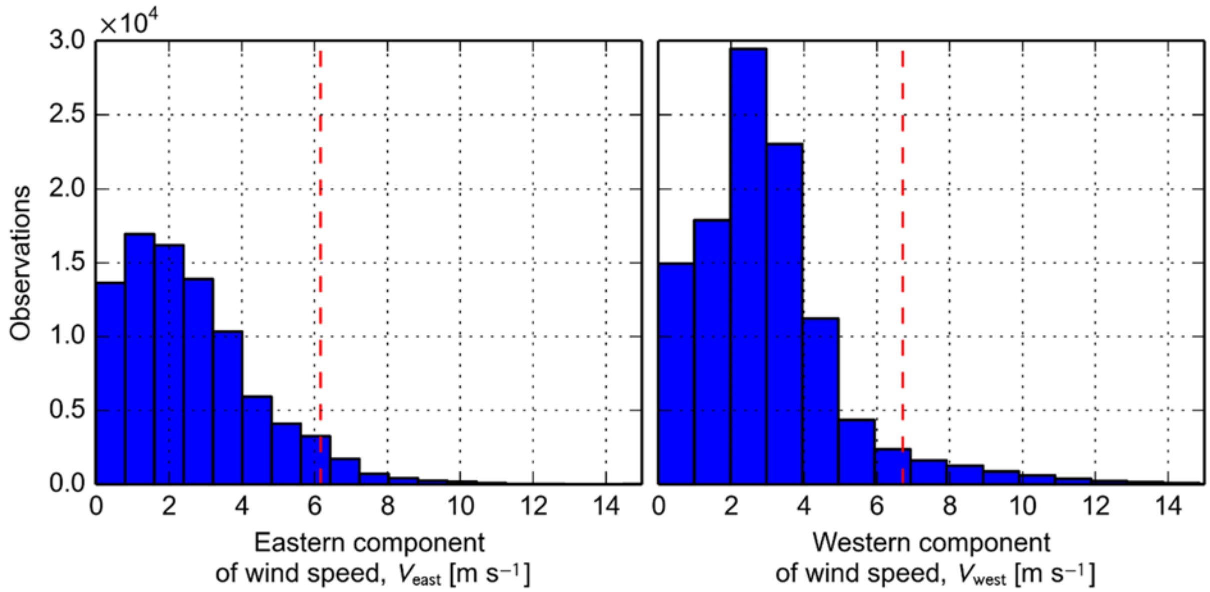


Figure 8-4 Eastern and western wind speed distributions, with the 95th percentile velocity indicated by a broken red line (- - -).

The dynamic pressure presented by the wind at the tunnel portals is calculated as

$$p_{\text{wind}} = \frac{1}{2} \rho V_{\text{wind}}^2 \quad (3)$$

where the density has a value of $\rho = 0.935$ Pa, based on an elevation of 1600 m and temperature of 38°C. The corresponding wind pressures are 17.76 Pa at the eastern portal and 21.12 Pa at the western portal. Based on this analysis a wind pressure of 20 Pa is assumed in the one-dimensional flow model.

E.1.3. Traffic fleet

The vehicle fleet is applicable for the design year (2035) and is derived from data provided by CDOT to ANA [31].The distribution of vehicle types is presented in Figure 8-5.

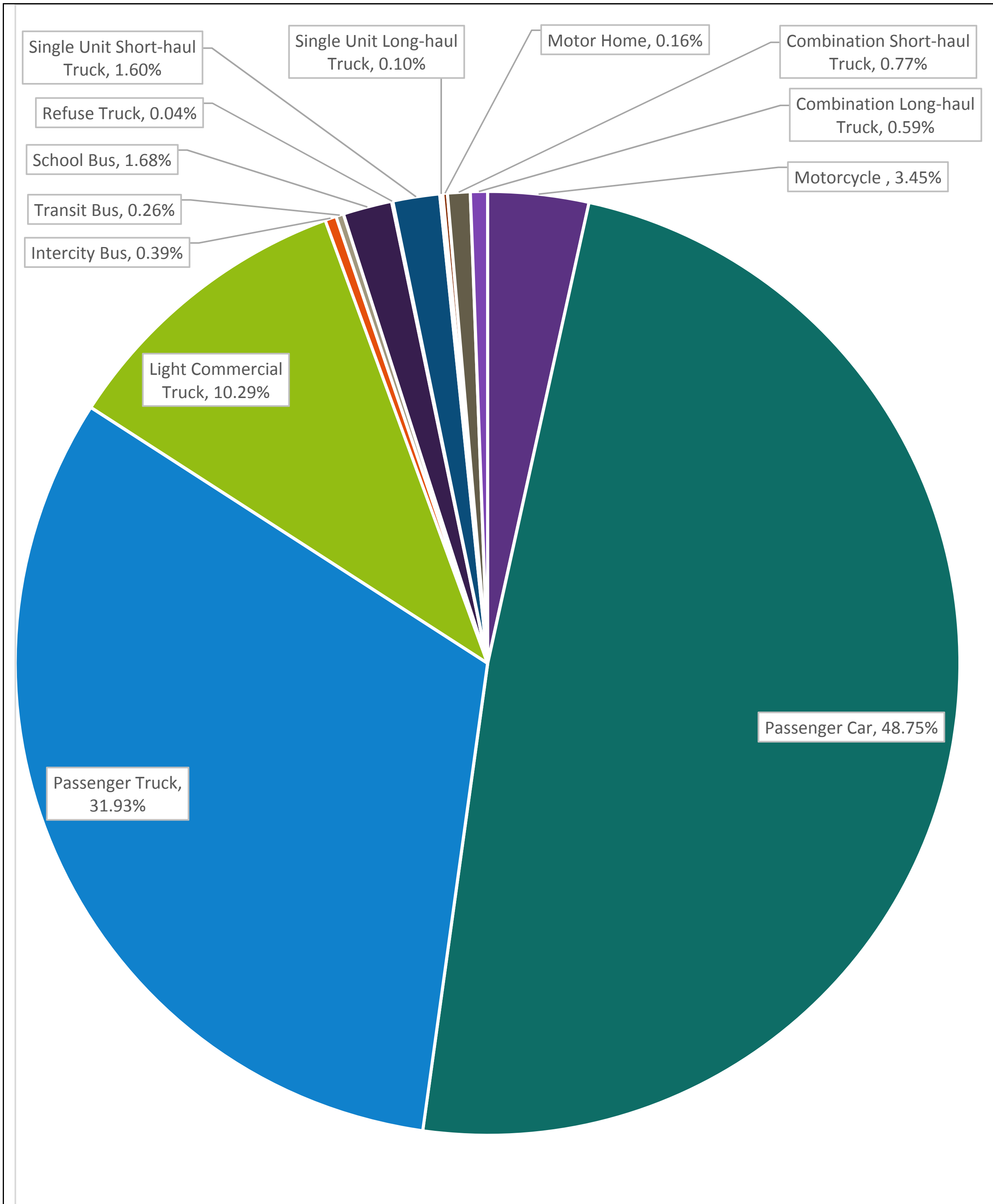


Figure 8-5 Distribution of vehicle types in traffic fleet.

E.1.4. Traffic Aerodynamic Parameters

The air flow induced through the piston effect is dependent upon the frontal areas and drag coefficients of the constituent vehicle types in the fleet. The assumed values for each vehicle type are listed in Table 8-5 below. The frontal area and drag coefficient of the motorcycle category is obtained from Cossalter [36], where a maximum drag-area ($C_D \times A$) of 0.7 is reported. The frontal areas of the remaining categories are based on the dimensions of the corresponding AASHTO Design Vehicles [35], and their drag coefficients are taken from PIARC (1995) [19].

Table 8-5 Vehicle aerodynamic parameters

I70 vehicle type	AASHTO design vehicle	Frontal area, A [m^2]	Drag coefficient, C_D
Motorcycle	-	1	0.7
Passenger Car	Passenger Car	2.8	0.35
Passenger Truck	Single-Unit Truck (min height)	8.2	0.8
Light Commercial Truck	Single-Unit Truck (max height)	10	0.8
Intercity Bus	Intercity Bus (Motor Coaches)	9.5	0.8
Transit Bus	City Transit Bus	8.3	0.8
School Bus	Conventional School Bus	7.8	0.8
Refuse Truck	Single-Unit Truck (max height)	10	0.8
Single Unit Short-haul Truck	Single-Unit Truck (max height)	10	0.8
Single Unit Long-haul Truck	Single-Unit Truck (max height)	10	0.8
Motor Home	Motor Home	8.9	0.8
Combination Short-haul Truck	Interstate Semitrailer	10.6	0.8
Combination Long-haul Truck	Interstate Semitrailer	10.6	0.8

E.2. Pollution Control

E.2.1. Control of Smoke and Hot Gases in Emergency

In the event of a fire within the covered section, vehicles downstream of the fire incident are assumed to be able to drive out safely ahead of the advancing front of smoke and hot gases. Passengers escaping from stationary vehicles trapped upstream of the fire can be protected by the tunnel ventilation system. Thrust will be generated by the jet fan system to induce sufficient flow velocity (the ‘critical velocity’) in the tunnel to counteract the momentum and buoyancy forces of the smoke and hot gases and push the smoke towards the exit portal.

E.2.2. Particular Modelling Assumptions

Fire Pressure Change

The airflow undergoes a local pressure reduction as it passes through a fire. This fire pressure drop is accounted for in the IDA Tunnel solver by means of a user input of a proportion of the fire power. A fire pressure drop factor of $f_{\mathrm{FPD}} = 0.2\ \mathrm{Pa\ MW^{-1}}$ is specified, based on research by Dutrieue and Jacques [38] for fires up to 30 MW.

Traffic density

Stationary traffic uproad of the fire is spaced at 6.06 m/PCU (e.g. density of 165 PCU/km, recommended by PIARC 2012 [20]. The equivalent number of passenger car units are listed for each vehicle category below.

Table 8-6 Passenger car units (PCU) equivalent for each vehicle category for the stationary traffic case.

I70 vehicle type	PCU equivalent [PCU]
Motorcycle	1
Passenger Car	1
Passenger Truck	1
Light Commercial Truck	1
Intercity Bus	3
Transit Bus	3
School Bus	3
Refuse Truck	3
Single Unit Short-haul Truck	3
Single Unit Long-haul Truck	3
Motor Home	3
Combination Short-haul Truck	3
Combination Long-haul Truck	3

E.2.3. Design Criteria

Critical Velocity

The primary design requirement is that the ventilation system generates the critical air velocity required to prevent backlayering of smoke and hot gases.

Installation Factor

Jet fan thrust is typically reported for unconfined conditions by the manufacturer. This thrust must be derated by an installation factor, which is a function of wall proximity and bypass velocity. An installation factor of 0.8 has been made based on manufacturer recommendations.

Ambient Temperature

Jet fan performance reduces with reducing air density, which will be at its lowest during the summer months when the air is warm. An ambient air temperature of 38°C is assumed, as this corresponds to the highest expected hourly temperature [30]

Altitude

As indicated above, air density changes with variation in temperature or humidity. Air density also changes with altitude by decreasing with increasing altitude. The project elevation being approximately 5,250ft.

Fire Size

The effective fire size to be controlled by the ventilation system is 30 MW convective heat load, based on the analysis in Section 5.

Fan Redundancy

At any given time it is expected that a proportion of the jet fans in the ventilation system will be out of service. NFPA 502 requires that failure or loss of availability of emergency ventilation equipment shall be considered. The UK standard BD 78/99 requires that at least 10% of fans or two units, whichever is greater, are unavailable. Two fans are assumed to be unavailable in each carriageway.

E.2.4. Analysis

Calculation of Critical Velocity

Backlayering can be prevented by ensuring a certain minimum air velocity (the critical velocity) is generated by the ventilation system. Kennedy (1995) [28] derives the following set of equations which can be solved for critical velocity v_c and fire temperature T_f based on a balance of momentum in the streamwise direction,

$$v_\mathrm{c} = \mathrm{Fr}^{-\frac{1}{3}}(1+0.0374m)^{0.8}\left(\frac{gHQ_\mathrm{f}f_\mathrm{c}}{\rho c_p A T_\mathrm{f}}\right)^{\frac{1}{3}} \tag{4}$$

$$T_\mathrm{f} = \frac{Q_\mathrm{f}f_\mathrm{c}}{\rho c_p A v_\mathrm{c}} - T_\mathrm{a} \tag{5}$$

where Fr is the critical Froude number, m is the gradient expressed as a percentage, g is acceleration due to gravity, H is tunnel height, Q_f is the fire heat release rate, f_c is the portion of fire heat transferred to air via convection, c_p is the specific heat capacity of air, A is the cross sectional area of the tunnel, T_f is the fire temperature and T_a is the ambient temperature. The numerical values for the inputs to the above equations are listed in Table 8-7. In the downstream portion of the tunnel, where the road gradient is positive, the buoyant smoke and hot gases will tend to flow in the streamwise direction, away from escaping pedestrians. However, for added conservatism, this beneficial effect is neglected by resetting positive gradients to zero.

Table 8-7 Input parameters for the calculation of critical velocity

Parameter	Value
Fr	4.5
m	Varies; see tunnel geometry in Table 8-2 and Table 8-3.

Parameter	Value
H	Varies; see tunnel geometry in Table 8-2 and Table 8-3.
Q_f	30 MW
f_c	1.0
c_p	1006 J kg^{-1} K^{-1}
A	Varies; see tunnel geometry in Table 8-2 and Table 8-3.
T_a	38°C (311.15 K)

The respective critical velocities for each tunnel segment are reported in Table 8-8 and Table 8-9 and Figure 8-6.

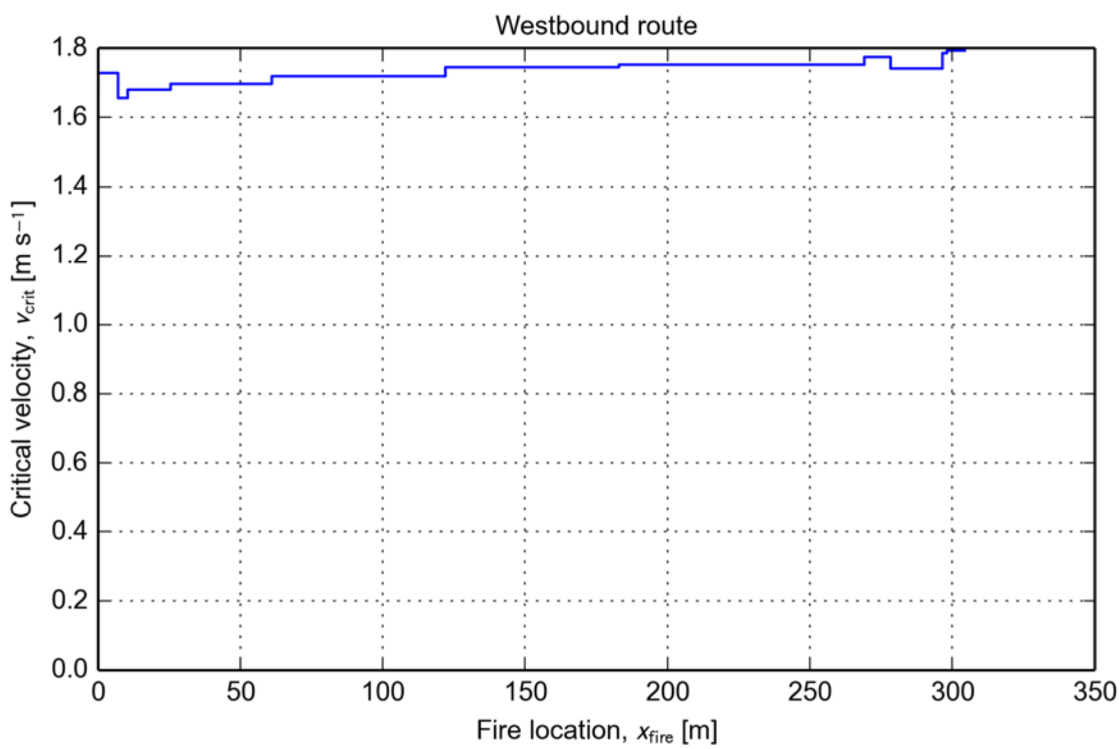
Table 8-8 Critical velocities in the westbound carriageway

Section	Section start [m]	Gradient [%]	Height [m]	Area [m^2]	Critical Velocity [m s^{-1}]
1	0	-0.9	6.51	242.46	1.68
2	7.03	-0.9	6.57	223.59	1.73
3	10.38	-0.9	5.49	207.23	1.66
4	25.57	-1.2	5.73	207.84	1.68
5	60.96	-1.2	5.74	201.49	1.7
6	121.92	-1.2	5.77	193.43	1.72
7	182.88	-1.2	5.79	183.66	1.75
8	269.1	-1.2	5.82	182.16	1.75
9	278.25	-1.2	6.11	185.63	1.77
10	296.53	-1.2	6.04	195.78	1.74
11	298.16	-1.2	6.78	207.89	1.78
exit	304.5	-1.2	6.86	207.89	1.79

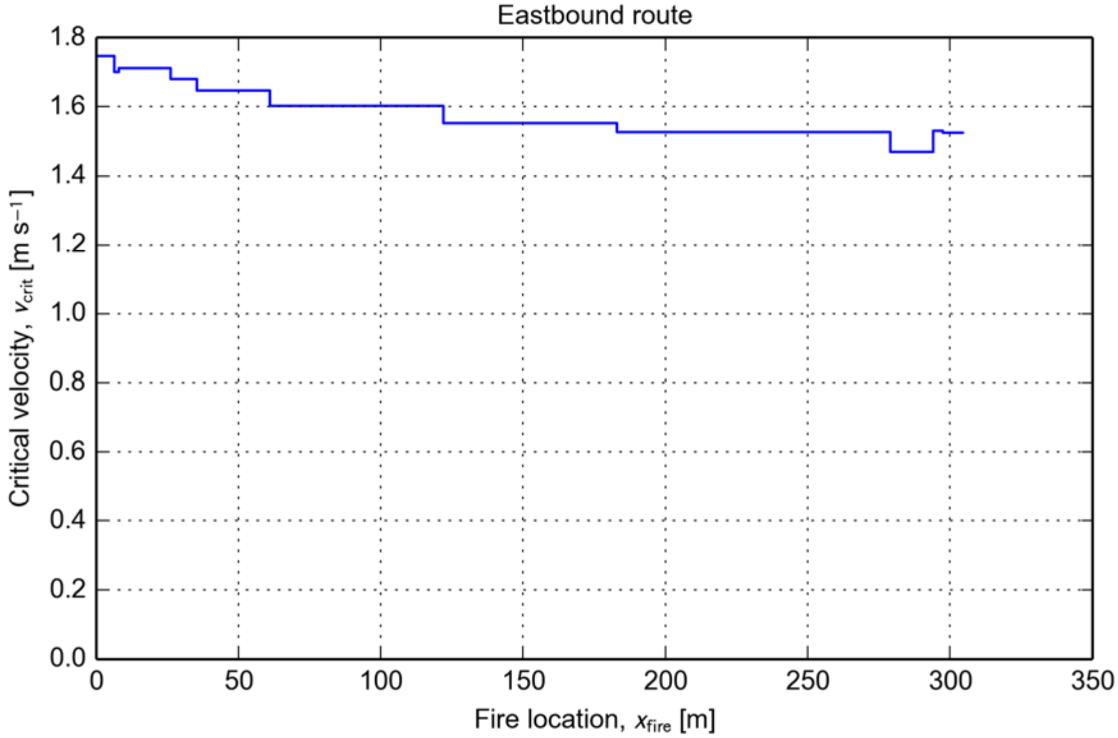
Table 8-9 Critical velocities in the eastbound carriageway

Section	Section start [m]	Gradient [%]	Height [m]	Area [m^2]	Critical Velocity [m s^{-1}]
1	0	1.2	6.86	209.33	1.79
2	6.34	1.2	6.78	197.48	1.81
3	7.97	1.2	6.04	188.02	1.76
4	26.26	1.2	6.11	186.4	1.77

Section	Section start [m]	Gradient [%]	Height [m]	Area [m^2]	Critical Velocity [m s^{-1}]
5	35.4	1.2	5.82	187.28	1.74
6	60.96	1.2	5.81	200.72	1.71
7	121.92	1.2	5.79	219.7	1.66
8	182.88	1.2	5.77	244.21	1.61
9	278.94	0.9	5.73	256.11	1.58
10	294.13	0.9	5.49	276.59	1.53
11	297.48	0.9	6.57	299.74	1.59
exit	304.5	0.9	6.51	299.74	1.58



(a)



(b)

Figure 8-6 Critical velocity for the westbound (a) and eastbound (b) routes.

Emergency Ventilation Scenarios

The one-dimensional flow solver IDA Tunnel v1.1 has been used to simulate a fire in the covered section and identify the number of jet fans required at the inlet portal to achieve the critical velocity.

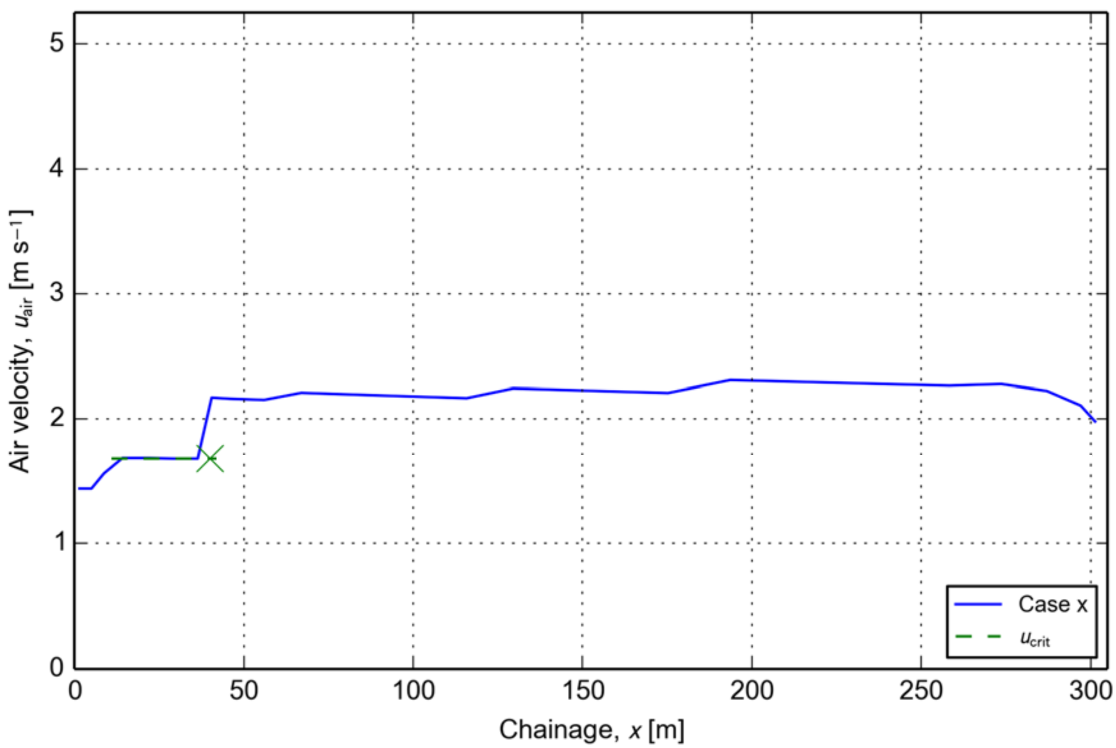
The most onerous operating case for the jet fan system in the westbound route is for a fire located 40 m from the inlet portal. Smoke and hot gases will naturally travel towards the entry portal due to the negative road gradient. The ventilation system must overcome buoyancy, traffic drag, tunnel resistance and wind pressure to direct hot gases downhill and out of the exit portal. Cases where the fire occurs closer than 40 m to the inlet have not been simulated; smoke and hot gases are expected to flow along the ceiling towards the inlet portal, clear of escaping road users.

The eastbound carriageway features a positive road gradient, and hence smoke and hot gases from a fire will naturally travel in the direction of the exit portal. However to ensure a conservative solution at this early stage of design, the positive road gradient has not been taken into account in the calculation of critical velocity. Additionally, there is a diffuser effect (reduction in air velocity) in the eastern direction due to the increasing cross-sectional area which must be overcome by the ventilation system. Hence the most onerous ventilation case is for a fire located near the exit portal. A distance of 40 m from the exit portal is assumed, as hot gases from fires located closer to the portal are expected to pass directly out of the portal due to buoyancy.

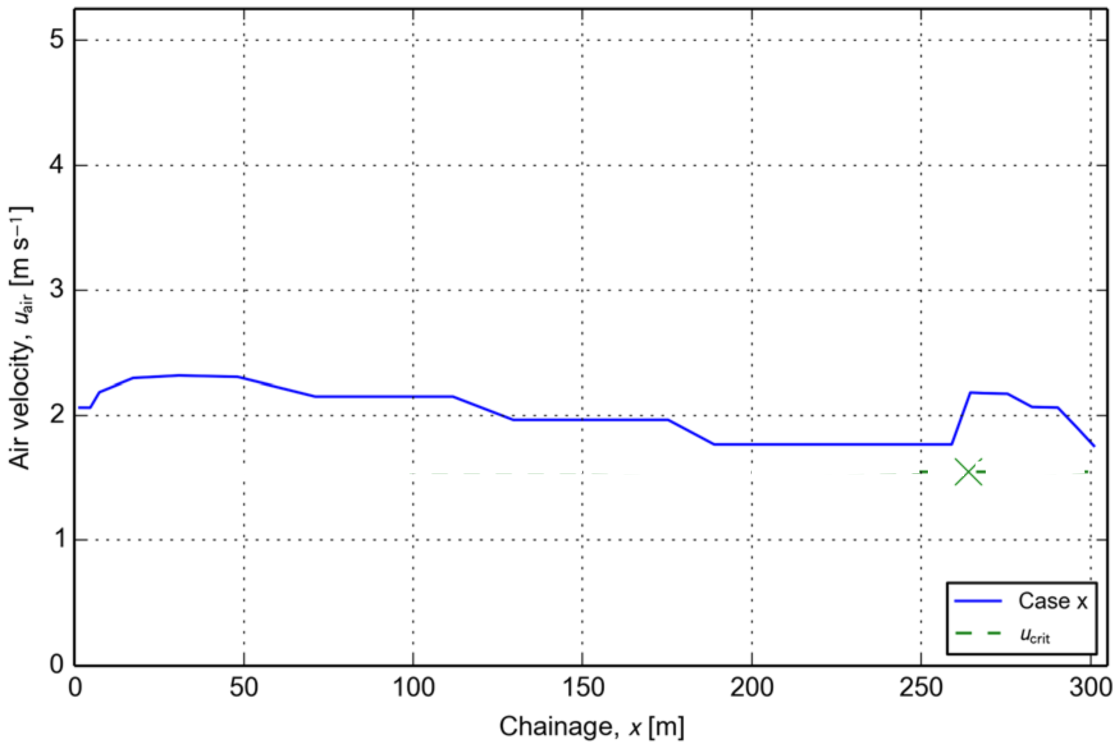
Table 8-10 Description of emergency ventilation scenarios

Case	Incident route	Fire location [m]	Number of jet fans	Number of jet fans operating
1	Westbound	40 (from entry)	13	11
2	Eastbound	40 (from exit)	12	10

In both cases the ventilation system achieves the required critical velocity at the site of the fire. This is demonstrated in Figure 8-7, where the respective air velocity distributions and critical velocity thresholds are compared.



(a) Case 1 – westbound, x_{fire} = 40 m



(b) Case 2 – eastbound, x_{fire} = 264 m (40 m from exit portal)

Figure 8-7 Comparison of ventilation controlled air flow with critical velocity at fire location for the single bore cases. The fire location is marked with a '×' symbol.

E.2.5. Summary of Ventilation System Performance in Emergency Scenario

A series of one-dimensional flow simulations have been carried out to assess the effectiveness of the proposed jet fan system in controlling smoke and hot gases in an emergency scenario. At this early stage of design, appropriately conservative assumptions have been made regarding design factors such as adverse wind pressure, fan installation factor, and ambient temperature. Simulation results predict that the proposed ventilation system is capable of controlling smoke for the most onerous design scenarios.

Appendix F. Drawings Used for development of Ventilation and FFFS concept

Preliminary reference drawing I-70 Roadway Plan. Partial cover lowered managed lanes. 12th December 2014

Reference drawing I-70 main line typical sections with cover. 2dn December 2014.

Estimate of cover cross sections

CAD Working files for the cover, as well as the roadway design files. Email sent by Daniel Liddle to Yenny Gomez, Simon Drake and Gary Clark

13599DES_Prof01_UPRR_Section 2.dgn

13599BRDG_Model_I-70-PartialCover.dng