Emergency Ventilation for Smoke Control in Roadway Tunnels (NCHRP Project 20-07 Task 363)

Louis Ruzzi – PennDOT District 11

Igor Maevski, PhD, PE - Jacobs

Agenda

- AASHTO T20 Technical Committee
- Roadway Tunnels Emergency Ventilation – Current Industry Knowledge and Practice
- Applicable Regulatory Standards and Guidelines
- ROAD TUNNEL FIRES - Main Design Fire Parameters
- Types of Road Tunnel Ventilation Systems and Conditions for Application, Configurations and Controls

AASHTO T20 Tunnels Technical Committee

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GARBAGE FIRE VIDEO

NCHRP Project 20-07 Task 363 Objectives

- To address the current knowledge and provide guidelines for emergency ventilation with references to NFPA 502 and other standards.
- Not to replace NFPA 502 Standard, but rather to provide guidelines to implement its requirements.
- A clear guidance to the owners and end users on emergency tunnel ventilation based on NFPA 502 standard requirements.
  - The scope of the developed document does not cover fire cases in rail and mass transit tunnels.

NCHRP Project 20-07 Task 363

- Helps DOTs for implementing best practices within their tunnel operation program in order to improve public and emergency responder safety.
- Choosing the type of ventilation system is one of the most important decisions when designing a tunnel.
- While every situation has its unique features, some general conclusions are drawn about the relative usefulness and efficiency of the various types of ventilation systems for smoke control.

Dr. Igor Maevski, PE, Jacobs, Principal Investigator

- Principal Member of NFPA 502 Technical Committee
- Chairman, ASHRAE Technical Committee TC5.9 on Enclosed Vehicular facilities (2014 – 2016)
- Chairman, ASHRAE Standards Committee SPC 217 for “Non-Emergency Ventilation in Enclosed Road, Rail and Mass Transit Facilities” (Since 2014)
- Author of NCHRP Synthesis 415 “Design Fires in Road Tunnels”

RECOMMENDED AASHTO GUIDELINES FOR EMERGENCY VENTILATION SMOKE CONTROL IN ROADWAY TUNNELS

Prepared for:

AASHTO Standing Committee on Highways

Prepared by:

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NCHRP PROJECT 20-07/TASK 363

RECOMMENDED AASHTO GUIDELINES FOR EMERGENCY VENTILATION SMOKE CONTROL IN ROADWAY TUNNELS

JACOBS

Table of Contents of the NCHRP Project 20-07 Task 363 Report (1)

Table of Contents of the NCHRP Project 20-07 Task 363 Report (2)

- Tunnel Ventilation Fans Utilization and Placement
- Effects of Ventilation on Tunnel Fires and Fire Sizes
- Fire Smoke Stratification and Length of Stratification and its Impact on Emergency Ventilation

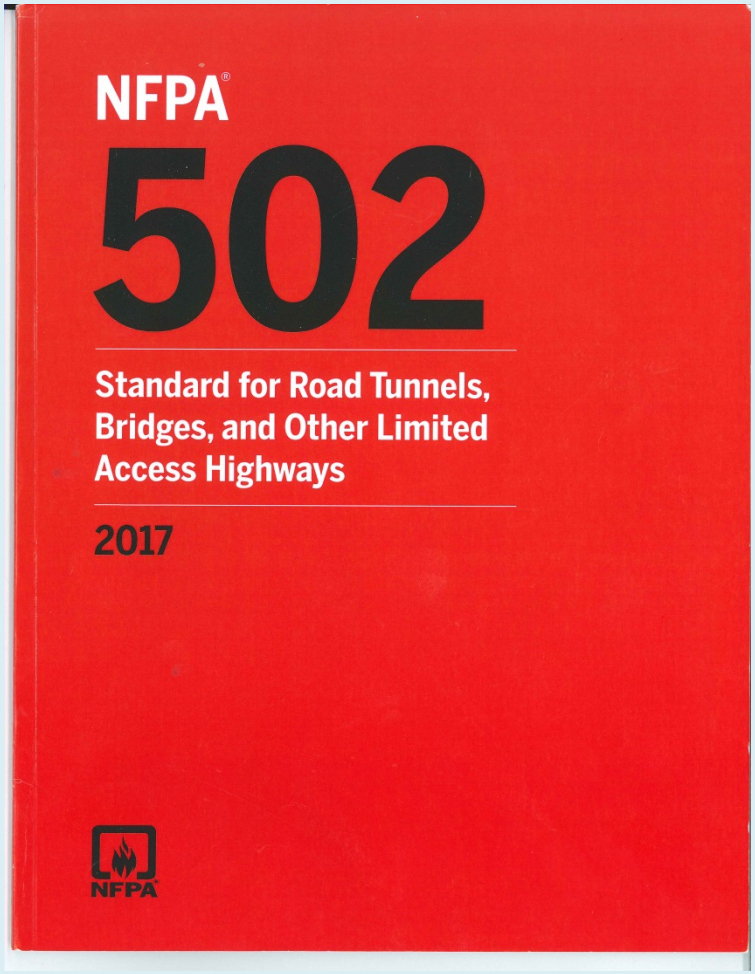
4. Tunnel Fire Detection and Warning Systems Design Guidelines
5. Tunnel Fire Suppression Design Guidelines

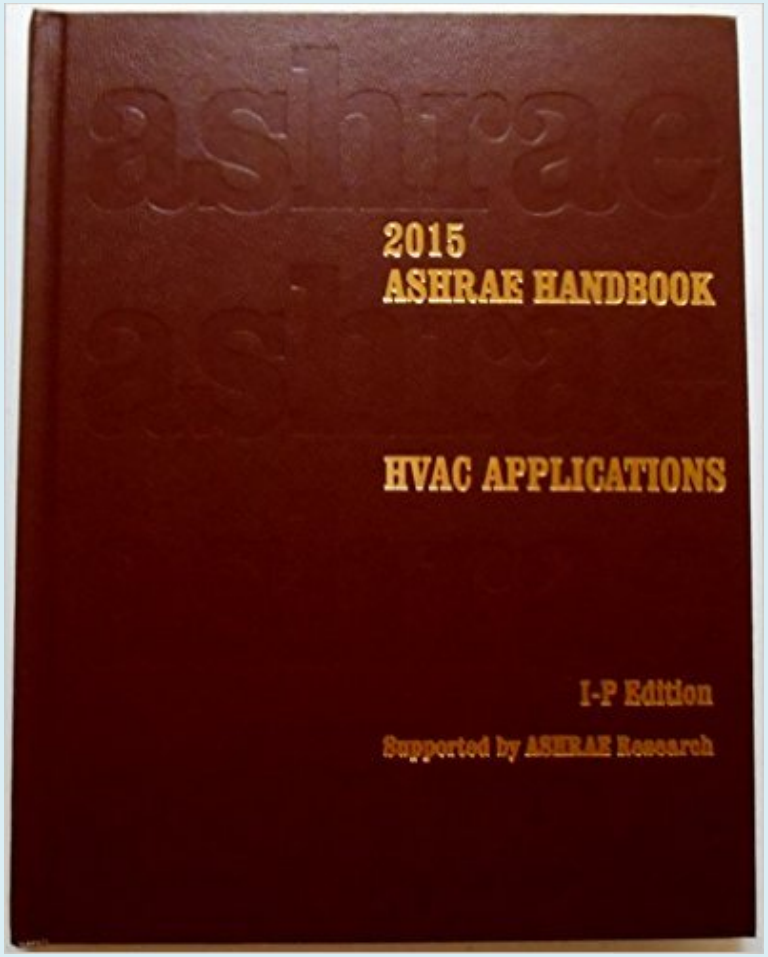
- Applicability of Tunnel Fire Suppression System
- Interaction Between Tunnel Fire Suppression and Ventilation Systems
  - i. Interaction Between Water Based Fixed Fire Suppression and Tunnel Ventilation Systems
  - ii. Interaction Between Firefighting Operation and Tunnel Ventilation System

6. Tunnel Emergency Ventilation Controls

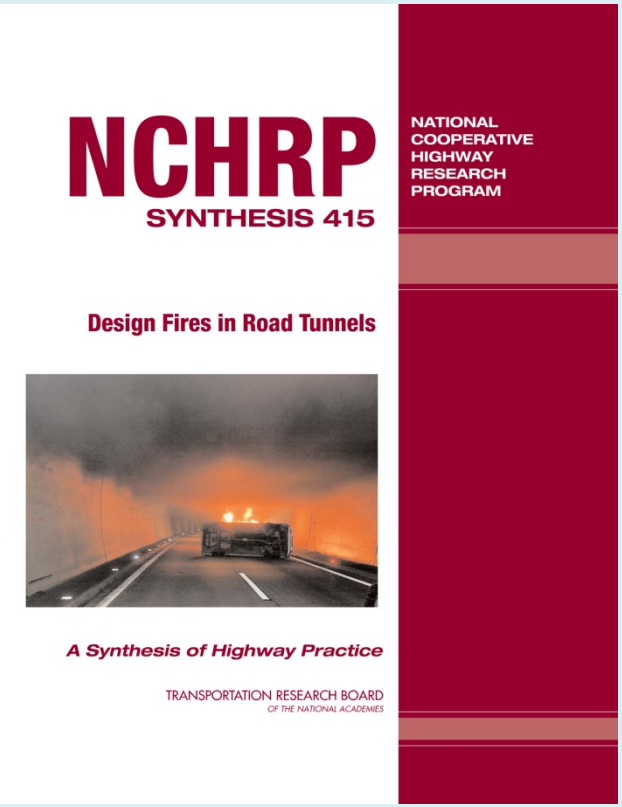
1. Introduction
2. Road Tunnel Fires
3. Tunnel Emergency Ventilation and Smoke Control
4. Tunnel Fire Detection and Warning Systems
5. Tunnel Fire Suppression
6. Tunnel Emergency Ventilation Controls

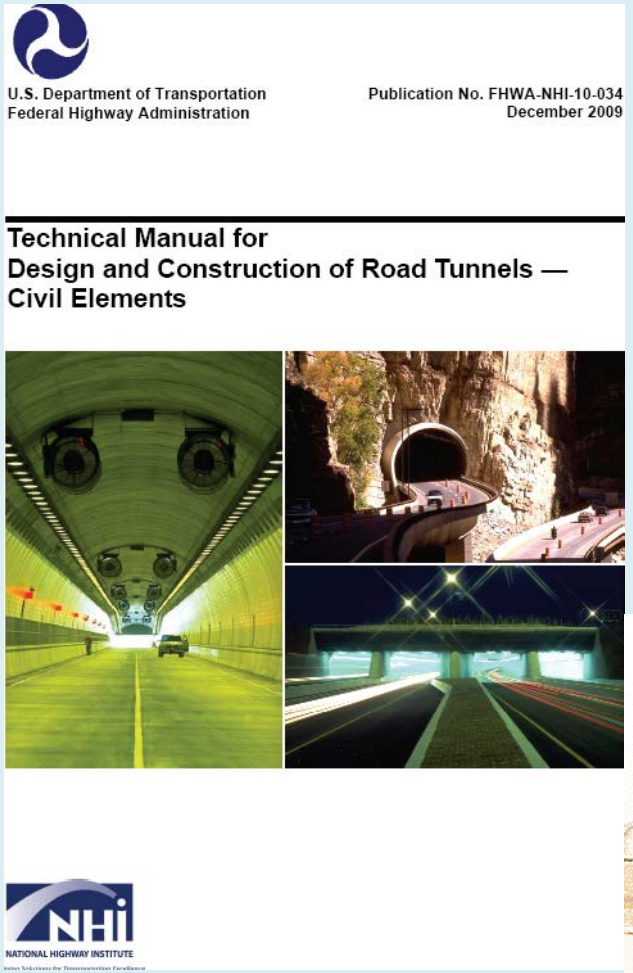
Roadway Tunnels Emergency Ventilation – US Standards and Guidelines

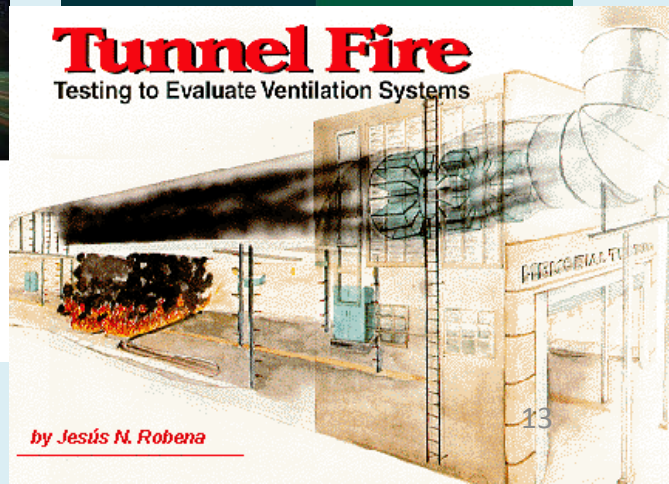




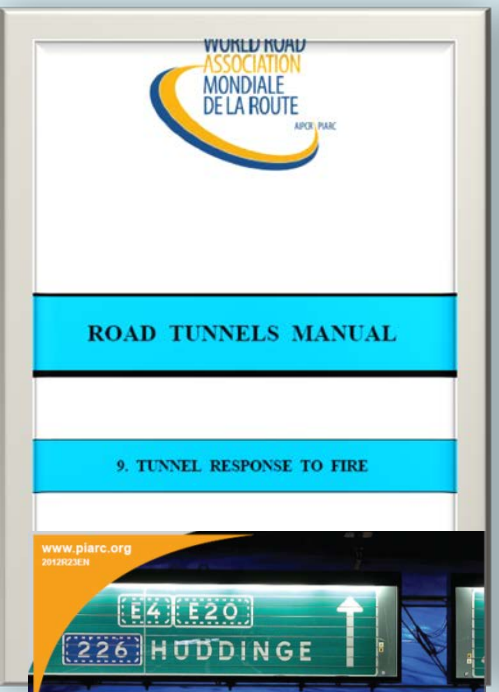
Other US Documents on Roadway Tunnels Emergency Ventilation

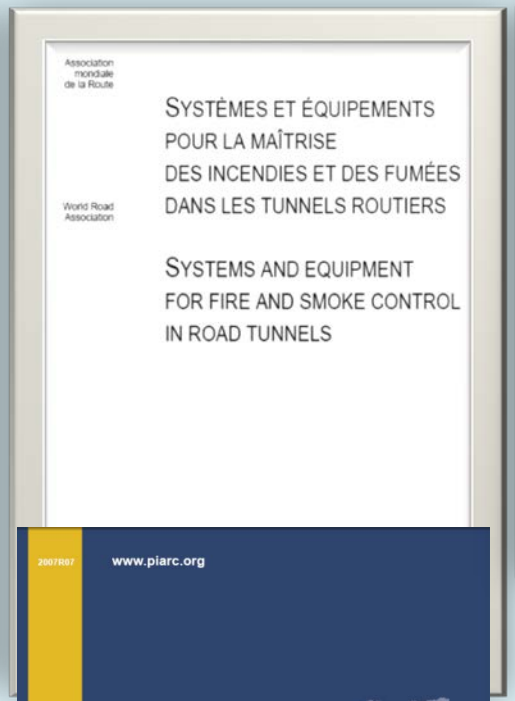


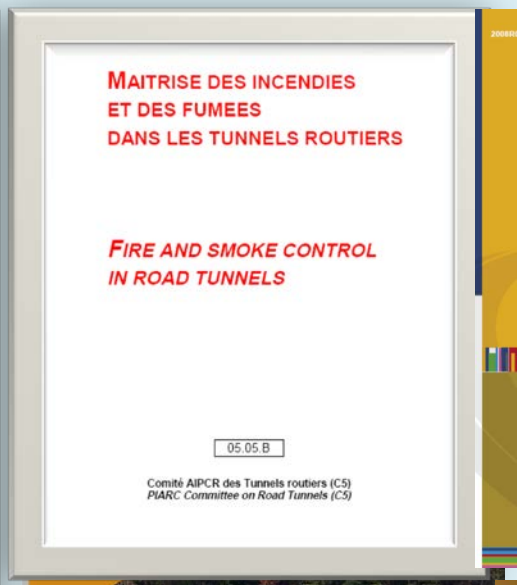


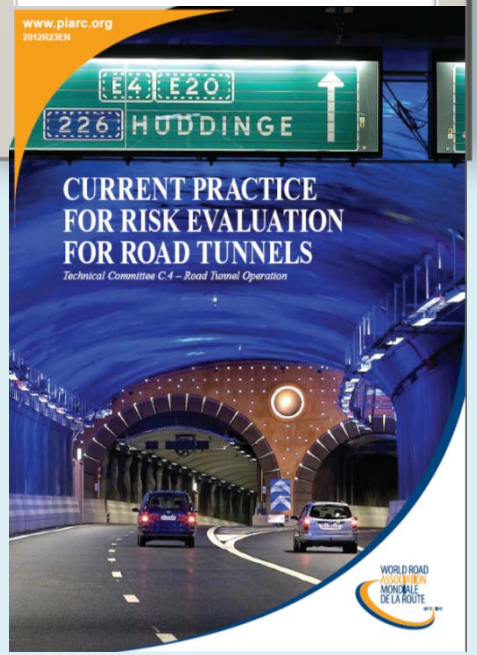


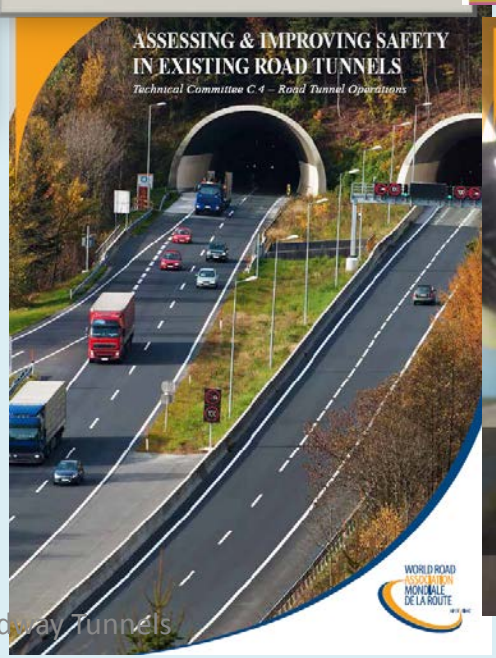
International PIARC Documents



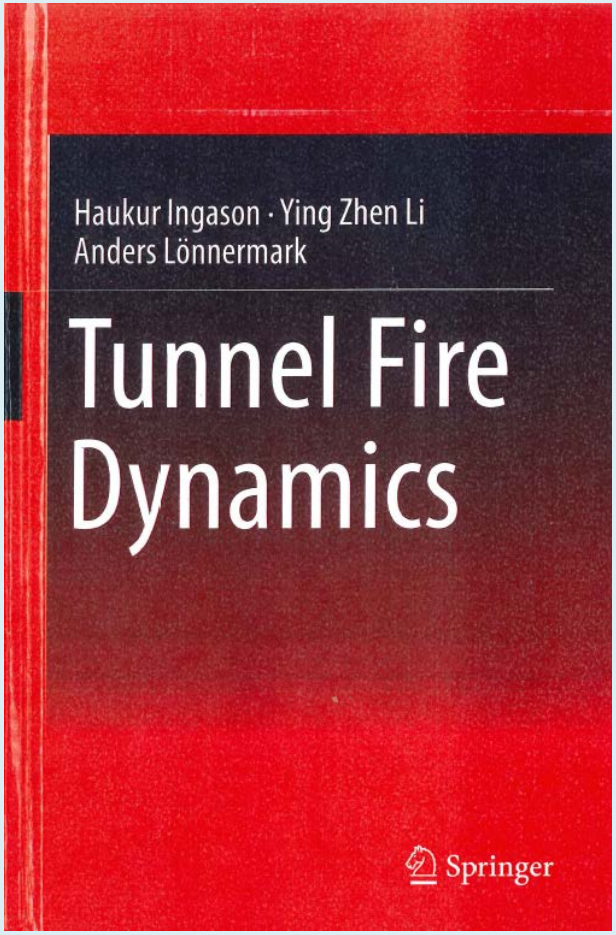


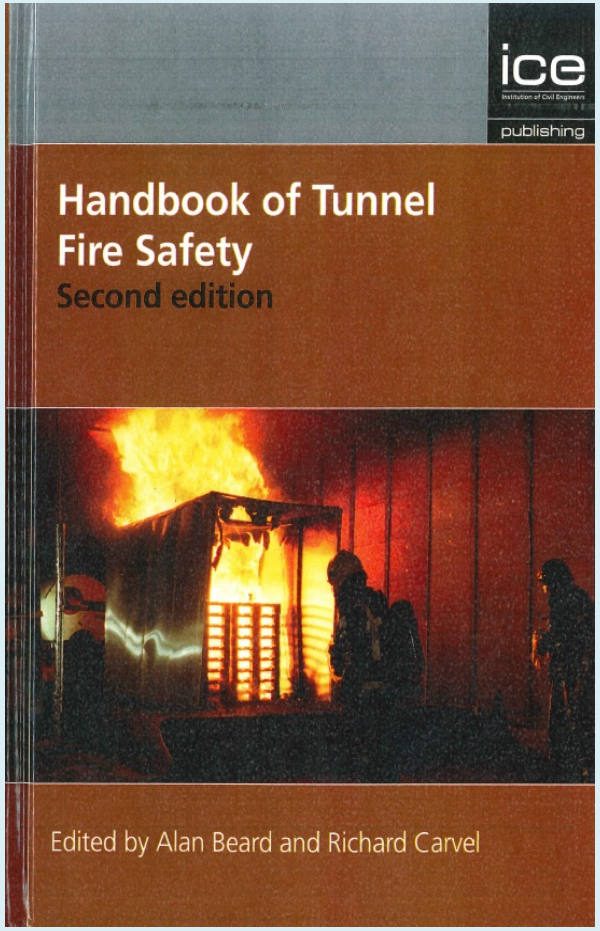






International Studies and Handbooks





International Standards and Guidelines

ISSN 0335-3931

French standard

NF EN 12101-3
9 October 2015

Classification Index: S 62-301-3

ICS: 13.220.20

Smoke and heat control systems — Part 3: Specification for powered smoke and heat control ventilators (Fans)

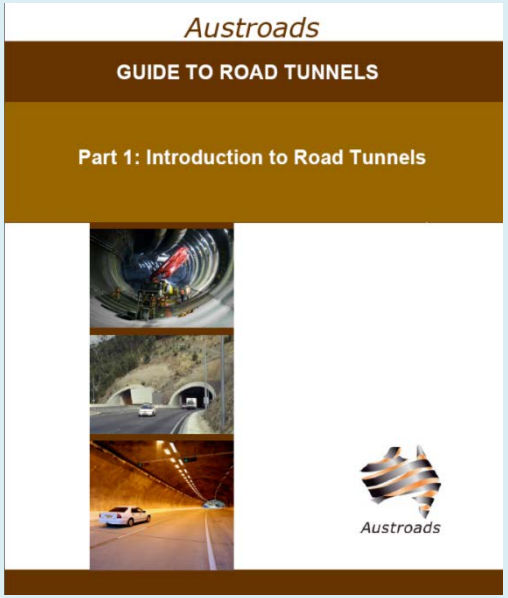
F : Systèmes pour le contrôle des fumées et de la chaleur — Partie 3 : Spécifications relatives aux ventilateurs pour le contrôle de fumées et de chaleur
D : Rauch- und Wärmefreihaltung — Teil 3: Bestimmungen für maschinelle Rauch- und Wärmeabzugsgeräte

French standard approved

by decision of the Director General of AFNOR.

Replaces the approved standard NF EN 12101-3 (classification index: S 62-303) of September 2002, which will remain in effect until May 2017.

Correspondence The European standard EN 12101-3:2015 has the status of French standard.



Austroads

GUIDE TO ROAD TUNNELS

Part 1: Introduction to Road Tunnels

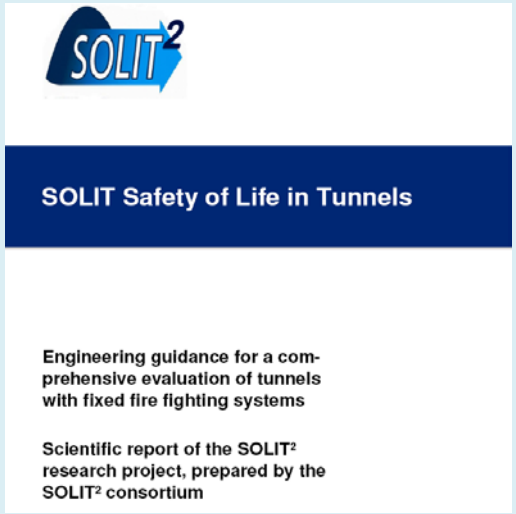
Austroads

OECD Studies in Risk Management

Norway

TUNNEL SAFETY

OECD



SOLIT²

SOLIT Safety of Life in Tunnels

Engineering guidance for a comprehensive evaluation of tunnels with fixed fire fighting systems

Scientific report of the SOLIT² research project, prepared by the SOLIT² consortium

RTA

Road tunnel design guideline

Part 1 – Concept design

FIRE SAFETY DESIGN

1. Introduction
2. Road Tunnel Fires
   - Main Design Fire Parameters
   - Impact of Fire Size on Smoke Management Requirements
3. Tunnel Emergency Ventilation and Smoke Control
4. Tunnel Fire Detection and Warning Systems
5. Tunnel Fire Suppression
6. Tunnel Emergency Ventilation Controls

Road Tunnel Fires – Main Design Fire Variables – Chapter 2.1

Time Dependant Design Fire Variables	Values Range		Design fire variables are a function of:
Fire Size - Maximum FHRR	1.5 – 300 MW [1] (5 – 1020 MBtu/hr)		Type of vehicle (cars, buses, HGV, Tanker; Alternative fuel)
Fire Growth Rate (slow, medium, fast, ultra fast)	0.002 – 0.178 kW/sec^2 as high as 0.331 kW/sec^2 measured at one test. 20 MW/min linear fire growth rate has been used for several tunnel projects where Flammable and Combustible Liquid Cargo were allowed to pass through the tunnel		Type of cargo including bulk transport of fuel
Fire Decay Rate	0.042 – 0.06 (min^{-1}) (Note that this parameter is often ignored for conservative evaluations)		Fire detection system and delay in activation of FLS systems
Perimeter of Fire	Car – truck perimeter or pool of liquid fuel spill		Ventilation profile
Maximum Gas Temperature at Ceiling	110 °C – 1350 °C (212 °F – 2462°F) (higher with new energy carriers)		Fire suppression system
Fire Duration	10 min – 6+ days		Tunnel geometry
Smoke and Toxic Species Production Rate	20 – 300 m^3/sec (42 – 640 kCFM)		- tunnel width, height, cross-section, length
Radiation	From 0.25 to 0.40 of total heat flux up to 5125 W/m^2 (1625 Btu/hr/ft^2)		- tunnel volume (available oxygen)
Flame Length	Up to full tunnel height		- shape of tunnel, grade - location of exits Tunnel drainage system

Sample Decision Making Chart on Design Fire Parameters

1. Are flammable vehicle cargo and hazardous materials allowed to travel through the tunnel?

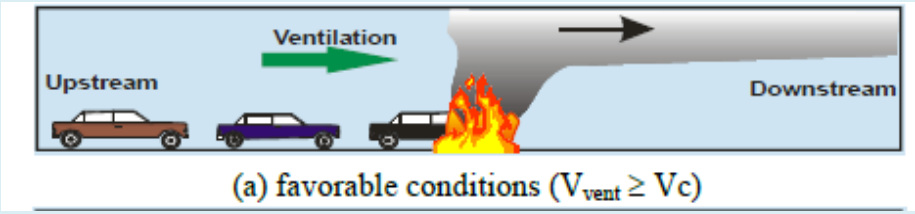
- *Yes* → **2. Are a fixed fire suppression and reliable detection system considered for tunnel protection?**
  - *Yes* → Ex: Consider a linear fire growth rate of 20 MW/min or faster for flammable or HAZMAT with the possible reduction of FHRR based on fire detection, sprinkler activation and sprinkler system design.
  - *No* → Ex: Consider a linear fire growth rate of 20 MW/min or faster for flammable or HAZMAT with the maximum FHRR specified in NFPA 502.
- *No* → **3. Are heavy goods vehicles (HGV) allowed to travel through the tunnel?**
  - *Yes* → **4. Are a fixed fire suppression and reliable rapid fire detection system considered for tunnel protection?**
    - *Yes* → Ex: Consider a quadratic fire growth rate of 187.6 W/s^2 to maximum FHRR specified in NFPA 502 with the possible reduction of FHRR based on fire detection, sprinkler activation and sprinkler system design.
    - *No* → Ex: Consider a quadratic fire growth rate of 187.6 W/s^2 with the maximum FHRR specified in NFPA 502.
  - *No* → **5. Is this a bus tunnel without HGV and FLC?**
    - *Yes* → **6. Are a fixed fire suppression and reliable rapid fire detection system considered for tunnel protection?**
      - *Yes* → Ex: Consider a quadratic fire growth rate of 100 W/s^2 to maximum FHRR specified in NFPA 502 with the possible reduction of FHRR based on fire detection, sprinkler activation and sprinkler system design.
      - *No* → Ex: Consider a quadratic fire growth rate of 100 W/s^2 with the maximum FHRR specified in NFPA 502.
    - *No* → **7. Is this a special tunnel? Is this tunnel for alternative fuel vehicles?**
      - *Yes* → Identification of alternative-fuel vehicles is critical and the tunnel should be evaluated on a case-by-case basis, which might be handled by risk analysis, computer modeling, experimental testing, or all of the above.
      - *No* → Unique type tunnel could be evaluated on a case-by-case basis.

A simplified example of tunnel fire safety risk and fire life safety system needs based on the tunnel length and traffic conditions

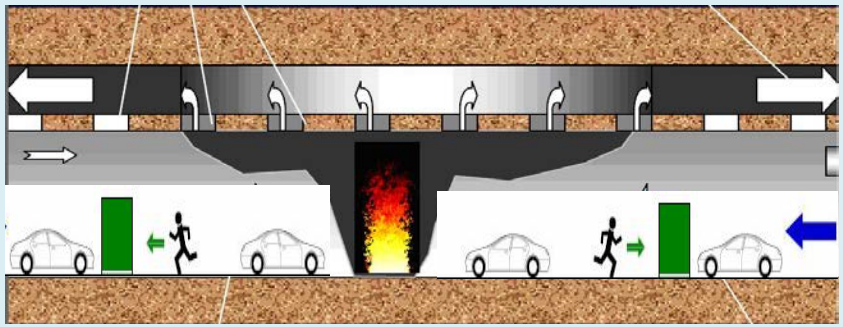
Category	Tunnel Length [ft]	*Uni-directional traffic*			*Bi-directional traffic*		
		w/HGV; w/FLC	*w/HGV; no FLC*	*no HGV; no FLC*	*w/HGV; w/FLC*	*w/HGV; no FLC*	*no HGV; no FLC*
X	< 300	*No Ventilation; No Fire Suppression*			*No Ventilation; No Fire Suppression*		
A	300 - 800	*Ventilation (suppression likely to protect structure)*	*No Fire Suppression (Ventilation questionable)*	*No Ventilation; No Fire Suppression*	*Ventilation; (suppression likely to protect structure)*	*No Fire Suppression (Ventilation questionable)*	*No Fire Suppression (Ventilation unlikely)*
B	800 - 1000	*Ventilation (suppression likely to protect structure)*	*No Fire Suppression (Ventilation likely)*	*No Fire Suppression (Ventilation questionable)*	*Ventilation, Fire Suppression*	*Ventilation; (suppression likely to protect structure)*	*No Fire Suppression; Ventilation required*
C	1000 - 3280	*Ventilation, Fire Suppression*	*Ventilation; (suppression likely to protect structure)*	*No Fire Suppression (Ventilation likely)*	*Ventilation, Fire Suppression*	*Ventilation; (suppression likely to protect structure)*	*No Fire Suppression; Ventilation required*
D	> 3280	*Ventilation, Fire Suppression*	*Ventilation, Fire Suppression*	*No Fire Suppression; Ventilation required*	*Ventilation, Fire Suppression*	*Ventilation, Fire Suppression*	*No Fire Suppression; Ventilation required*

1. Introduction
2. Road Tunnel Fires
3. Tunnel Emergency Ventilation and Smoke Control
   - Types of Road Tunnel Ventilation Systems
   - Tunnel Ventilation Systems Conditions for Application and Configurations
     - i. Tunnel Length, geometry, grades
     - ii. Traffic Conditions
   - Tunnel Ventilation Fans Utilization and Placement
   - Effects of Ventilation on Tunnel Fires and Fire Sizes
   - Fire Smoke Stratification and Length of Stratification and its Impact on Emergency Ventilation
4. Tunnel Fire Detection and Warning Systems
5. Tunnel Fire Suppression
6. Tunnel Emergency Ventilation Controls

Two Commonly Used Smoke Ventilation Concepts in Road Tunnels



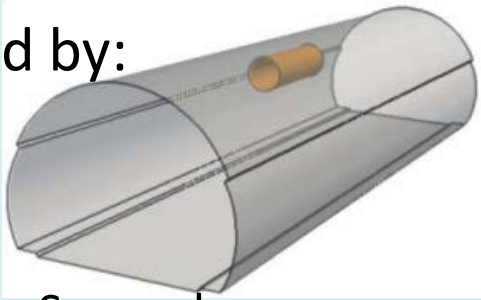
- Longitudinal Ventilation – Critical Velocity Concept

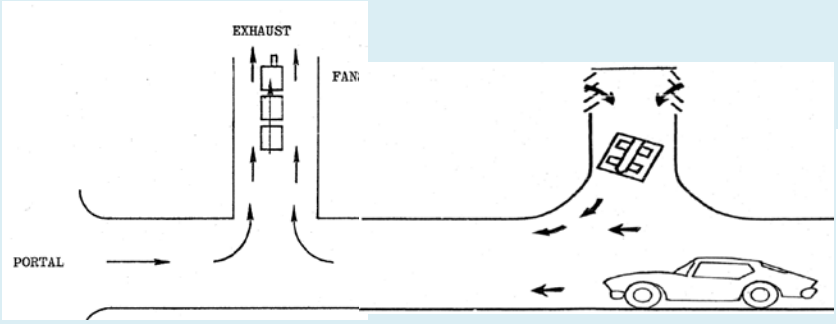


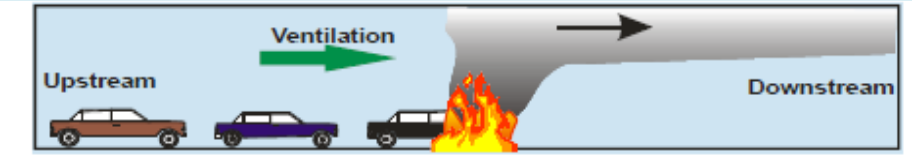
- Extraction Ventilation – Smoke Stratification Concept

Longitudinal Ventilation Concept

- Directing smoke along the tunnel in the opposite direction of egress by completely pushing the smoke to one side of the fire
  - Longitudinal ventilation can be accomplished by:
    - Injection
    - Central fans using Coanda effect
    - Jet fans mounted within the tunnel
    - Nozzles (often installed at the portals and called a Saccardo System)
    - A combination of injection and extraction at intermediate points.

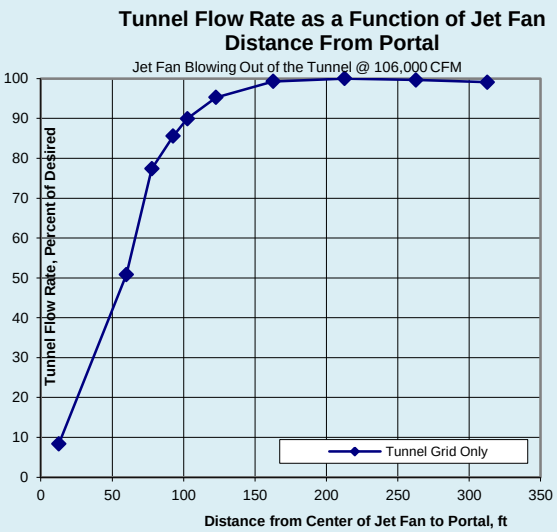






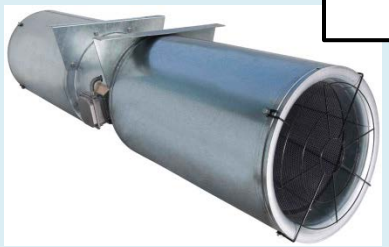
(a) favorable conditions ($V_{vent} \geq Vc$)

Example of Design process for Consideration of Longitudinal Ventilation for the Road Tunnel Ventilation System Selection

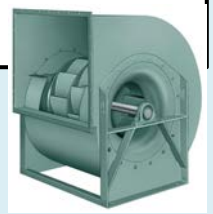


Other Constrains:

- Space constraints
- Shaft excavation needs
- Air ducts length limitations
- Tunnel width and its impact on lateral ventilation
- Construction and operating costs

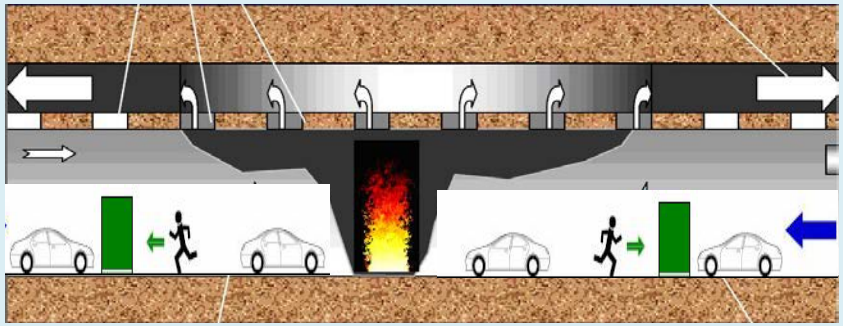


1. Is this a uni-directional tunnel?
   - *No* → Consider transverse or semi-transverse exhaust, or single point extraction ventilation scheme for smoke and hot gas management or modification of longitudinal ventilation
   - *Yes* ↓
2. Can the traffic management system manage traffic downstream of the fire event?
   - *No* → Consider transverse or semi-transverse exhaust, or single point extraction ventilation scheme for smoke and hot gas management or modification of longitudinal ventilation
   - *Yes* ↓
3. Will the tunnel NOT be used for bi-directional traffic during construction, maintenance or other events?
   - *No* → Consider transverse or semi-transverse exhaust, or single point extraction ventilation scheme for smoke and hot gas management or modification of longitudinal ventilation
   - *Yes* ↓
4. Are tunnel air velocities less than (10 m/s [2000 fpm]) during normal, congested and fire emergency?
   - *No* → Consider transverse or semi-transverse exhaust, or single point extraction ventilation scheme for smoke and hot gas management or modification of longitudinal ventilation
   - *Yes* ↓
5. Is this a short tunnel less than 800 ft (240 m) long with constant uphill grade of 4% or more and no flammable and combustible fuel vehicles?
   - *No* → Consider transverse or semi-transverse exhaust, or single point extraction ventilation scheme for smoke and hot gas management or modification of longitudinal ventilation
   - *Yes* → Consider longitudinal ventilation



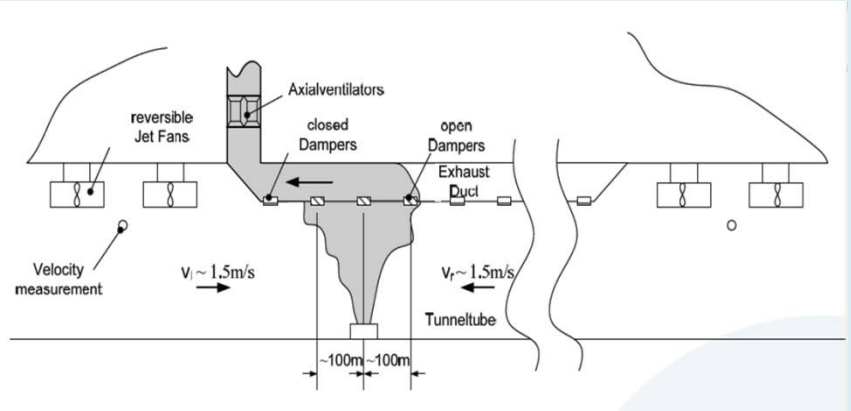
Extraction Ventilation Concept

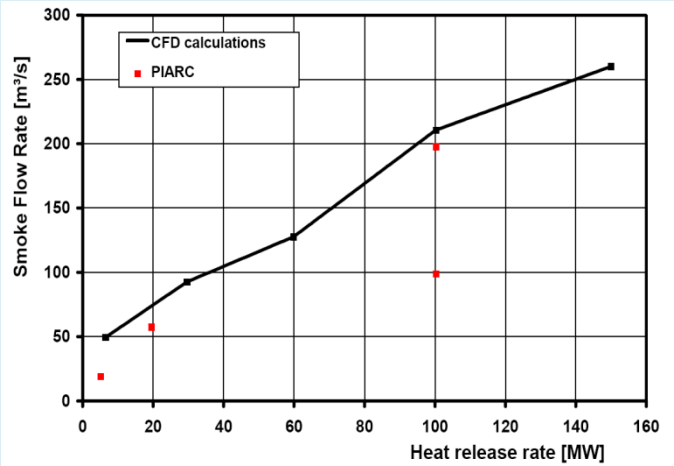
- Extracting smoke at the fire location by keeping the smoke stratification intact, leaving more or less clean and breathable air suitable for evacuation underneath the smoke layer to both sides of the fire



Extraction Ventilation Concept

- Extracting smoke at the fire location
  - Applicable to bi-directional or congested unidirectional tunnels.
  - Typically achieved by zoned transverse ventilation or single point extraction.
  - Typically requires exhaust ventilation ducts and a system capable of localizing hot gases and smoke and extracting them at the fire location using exhaust high temperature rated ventilation fans.





Smoke Stratification?

Diesel fuel pan fire of 5 MW in I-90 tunnel in Seattle

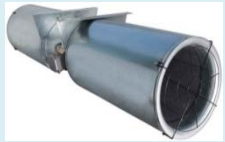
Winnipeg Transit Bus 485 on Fire
(Source: https://youtu.be/U0nK2gfLJqc)

Strategies for Smoke Control

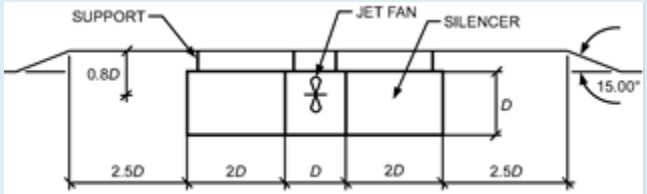
LONGITUDINAL VENTILATION		
TUNNEL TRAFFIC CONDITIONS	Evacuation Phases	Fire-fighting Phase
Unidirectional tunnel <u>without</u> traffic congestion	• Avoid backlayering of smoke: Provide sufficient longitudinal air velocity (critical velocity) in the same direction as traffic flow.	
Unidirectional tunnel with traffic congestion	The smoke stratification must not be disturbed: • Longitudinal air velocity quite small • No jet fans working in fire / smoke zone	Avoid backlayering of smoke: • Higher longitudinal velocity • Direction of airflow adaptable
Bi-directional traffic (Not recommended in the US and many other countries)		

EXTRACTION VENTILATION SYSTEMS	
TUNNEL TRAFFIC CONDITIONS	PRINCIPLE FOR SMOKE EXTRACTION
Unidirectional tunnel <u>without</u> traffic congestion	• Direct airflow in direction of traffic upstream of the extraction zone to prevent or at least minimize backlayering of smoke.
Unidirectional tunnel with traffic congestion	• Zero longitudinal velocity at the center of the extraction zone by having airflow rates from both sides towards the extraction zone. • Preserve stratification and confine the smoke to the region of the extraction zone.
Bi-directional traffic	

Tunnel Ventilation Fans Utilization and Placement



- Jet Fans (Longitudinal Ventilations)

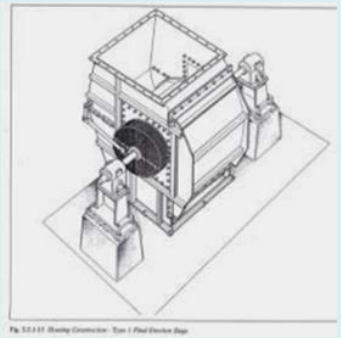


Nominal FHRR, MW (MBtu/h)	Temperature at Central Fans,[a] °C (°F)	Temperature at Jet Fans,[b] °C (°F)
20 (68)	107 (225)	232 (450)
50 (170)	124 (255)	371 (700)
100 (340)	163 (325)	677 (1250)

FHRR = Fire heat release rate in **Memorial Tunnel Tests**
[a]Central fans located 700 ft (213 m) from fire site.
[b]Jet fans located 170 ft (52 m) downstream of fire site.

Saccardo Nozzle (Longitudinal Ventilation)

- Transverse Ventilation Fans
- Centrifugal
- Axial Fans



	Fire size, MW (MBtu/h)	Distance upstream of fire, m (ft)	Distance downstream of fire, m (ft)
Distance at which Jet Fans are assumed to be destroyed by a tunnel fire	5 (17)		
	20 (68)	10 (32.8)	40 (131.2)
	50 (171)	20 (65.6)	80 (262.5)
	100 (341)	30 (98.4)	120 (393.7)

Effects of Ventilation on Tunnel Fires and Fire Sizes

- Impact of Ventilation on Fire Size and Fire HRR
- Impact of Ventilation on Fire Growth Rate

Ventilation Rate	Growth Rate
Less than 1 m/s	About 5 MW/min
About 3 m/s	About 15 MW/min
About 6 m/s	About 10 MW/min

- Ventilation could cause flame deflection which leads to the chance that the fire might spread to other vehicles and threaten the integrity of the tunnel structure on a larger surface, assuming the ventilation cooling effect and reduction in radiation at the source are insignificant
  - Due to increased ventilation, the fire development for a car can be slowed if the fire is ignited at the front of the car.
    - This is in contrast to the accepted view of supposed accelerated development due to ventilation.
  - The influence of increased ventilation on the observed fire behavior depends on the ignition location.
    - Note that 95% of fires begin in the engine compartment (i.e. at the front).

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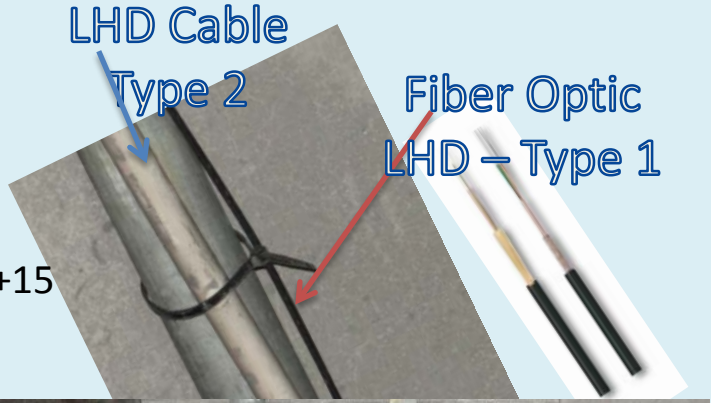
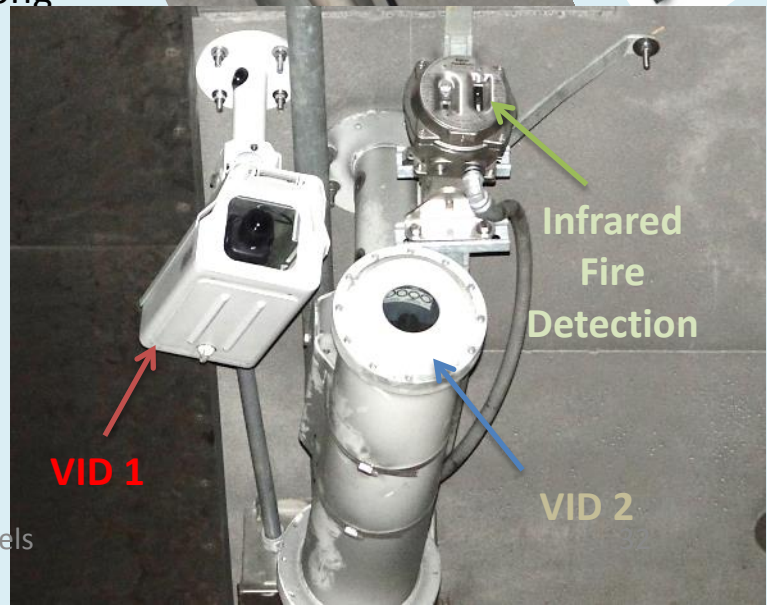
Tunnel Fire Detection and Warning Systems

- Video Image Detection (VID) System
  - Flame Detection & Smoke Detection
  - Two Cameras installed, paired together, 120ft to the west of the pan location
- Video Infra-Red System
  - Two Detectors; One 120ft to the west, One 30ft to the east of the fire
    - The cameras are facing one another and the fire
- Spot Heat Detection
- Linear Heat Detector
  - Fiber Optic Reports Raises in Temperature +5, +10, & +15 Degrees Above Ambient
  - Linear Heat Detection with temperature sensors along





Summary of Fire Detection Tests Results

Detection systems	Fire Detection Time (s)	Missing Detection	Nuisance alarms
Infra-Red fire detection	0 - 68	Once	No
Linear Heat Detection Type 1	1 - 115	None	Once
Linear Heat Detection Type 2	11 - 95	None	No
Video flame and smoke detection Type 1	10 - 233	Yes	Numerous
Video flame and smoke detection Type 2	56 - 140	Yes	Numerous
Existing Spot Heat Detection	47 - 600	Yes	No

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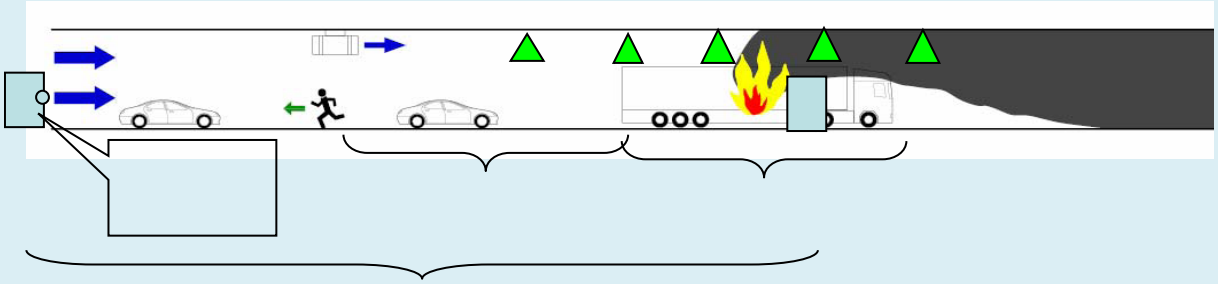
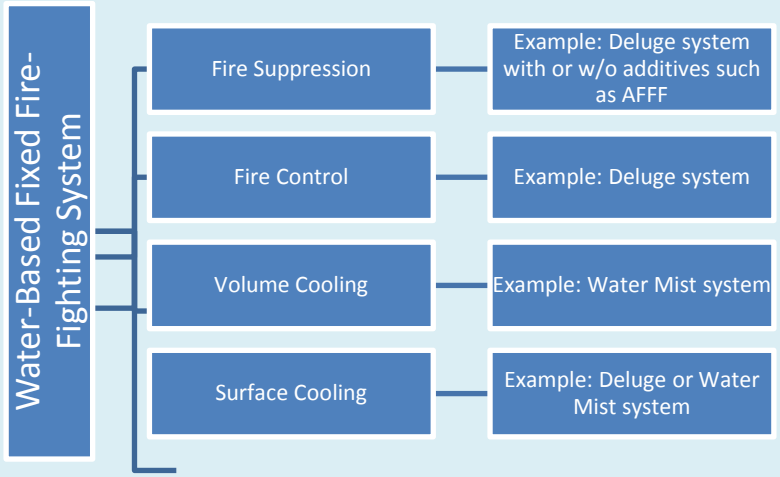
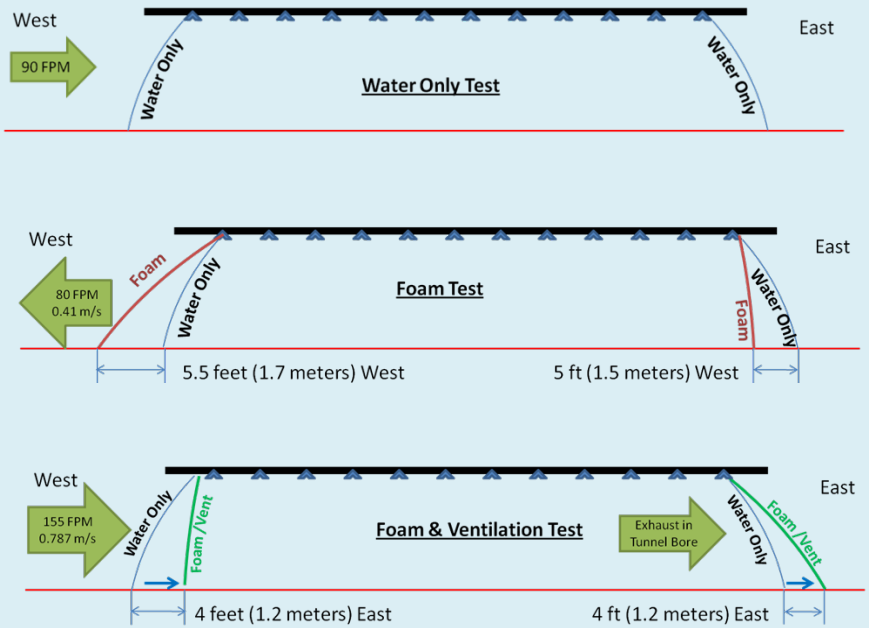
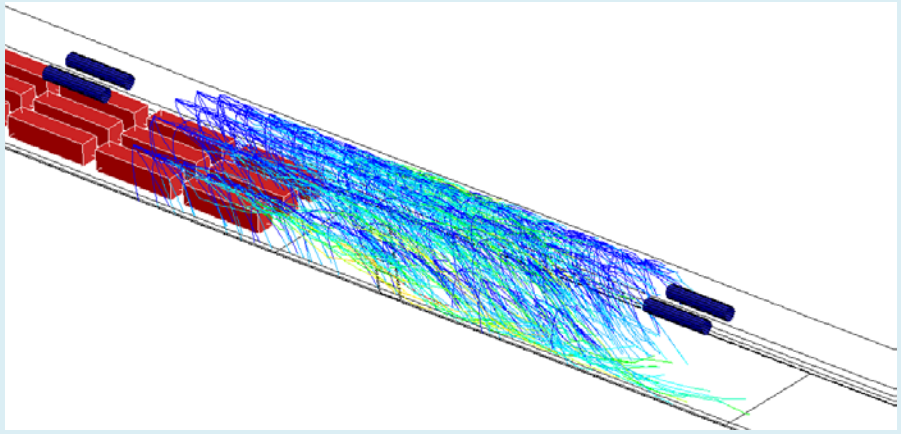
   - Interaction Between Tunnel Fire Suppression and Ventilation Systems
     - i. Interaction Between Water Based Fixed Fire Fighting and Tunnel Ventilation Systems
     - ii. Interaction Between Firefighting Operation and Tunnel Ventilation System
6. Tunnel Emergency Ventilation Controls

Tunnel Fire Suppression

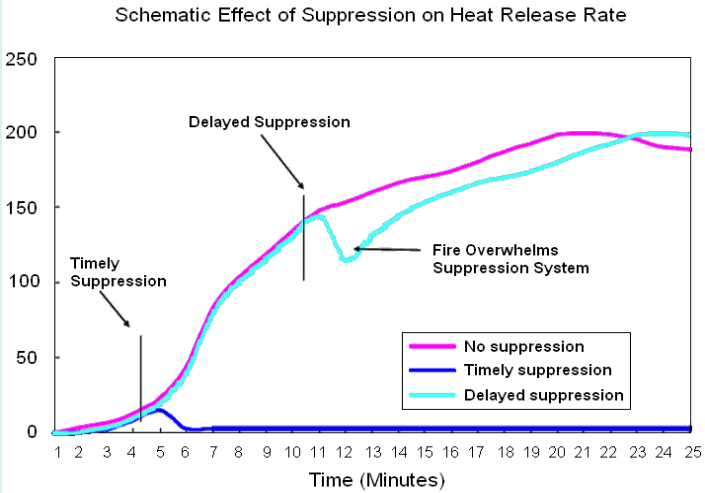


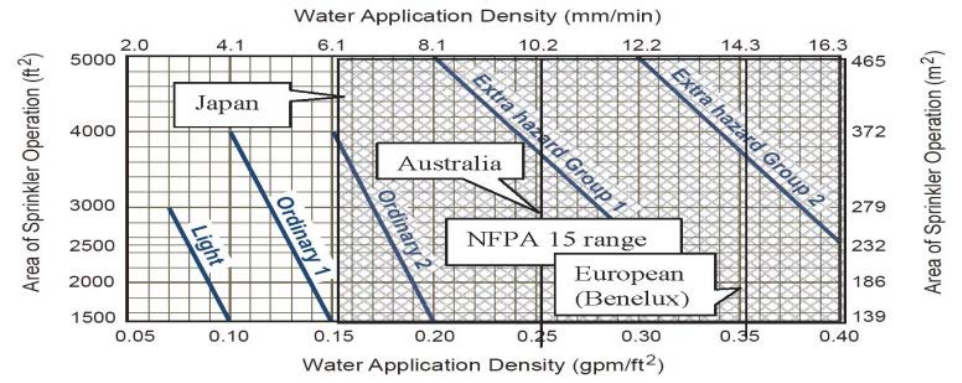






Applicability of Tunnel Fire Suppression System





- Applicability of Fixed Fire Suppression System depends on objectives and on:
  - Potential fire risk
  - Level of protection
  - Other safety measures in the tunnel
  - Tunnel geometry
  - Ventilation/wind conditions during a fire, including interaction with emergency ventilation
  - Type and performance of the fire detection systems
  - Activation mode of the suppression system
  - Any restrictions in positioning and fixing the pipework or nozzles
  - Distance to emergency exits
  - Signage and lightning
  - Thermal conditions in the tunnel and its surroundings
  - Any specific requirements for the operation of the tunnel

Advantages and Challenges of a Fixed Fire Fighting System (FFFS)

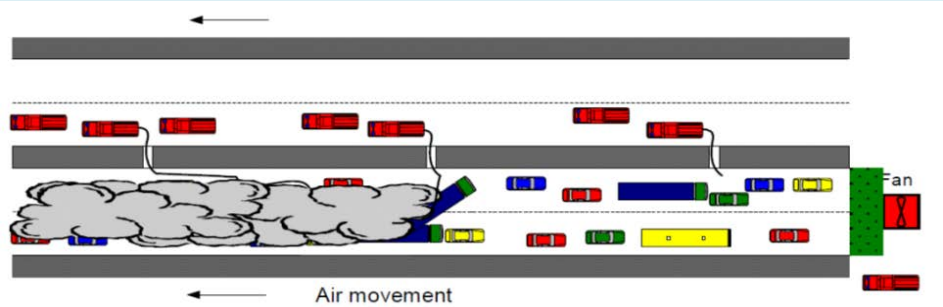
Advantages of FFFS	Challenges of FFFS
General	
• A FFFS is designed to react on an early stage of the fire. • Takes fire under control not allowing it to further grow, or grow slowly, or extinguishing a small fire before the fire department arrives. • Protection of tunnel users and structure. Duration of the fire can be limited and the structure of the tunnel will be subjected to less harsh conditions. • Protection of First Responders	• Possible loss of visibility (reduced visibility) especially on an early stage when people evacuate. When the sprinkler system is activated on an already large fire, a large amount of water will be evaporated, diminishing the visibility further. • Incomplete combustion creates smoke, gases and steam. Studies needed on critical time to activate the FFFS to protect the tunnel structures. • Creates slippery environment when water applies. May create panic when malfunctions with accidental water release.
Extraction Ventilation (including single point extraction)	
• Reduced fire size. • Reduced fire duration. • See 'General' for additional information.	• Destroys stratification of hot air, which makes ceiling extraction inefficient and evacuation difficult. • Increased mass of air / water mixture to move results in increased ventilation rate for extraction ventilation.
Longitudinal Ventilation – Unidirectional Tunnel with Manageable Traffic	
• Reduced fire size may result in reduced ventilation rate. • Cools environment and protect fan units from high temperature. • See 'General' for additional information.	• Increased mass of air / water mixture to move – increase ventilation rate. • Overcome water curtains created by the FFFS system – increase ventilation rate. • Displacement of water particles away from the fire – increase number of FFFS zones for activation.
Longitudinal Ventilation – Unidirectional Tunnel with Unmanageable Traffic or Bidirectional Tunnel	
• Protects tunnel structure.	• Destroys stratification, making evacuation difficult (maybe impossible) on both sides of the fire once the FFSS is activated.

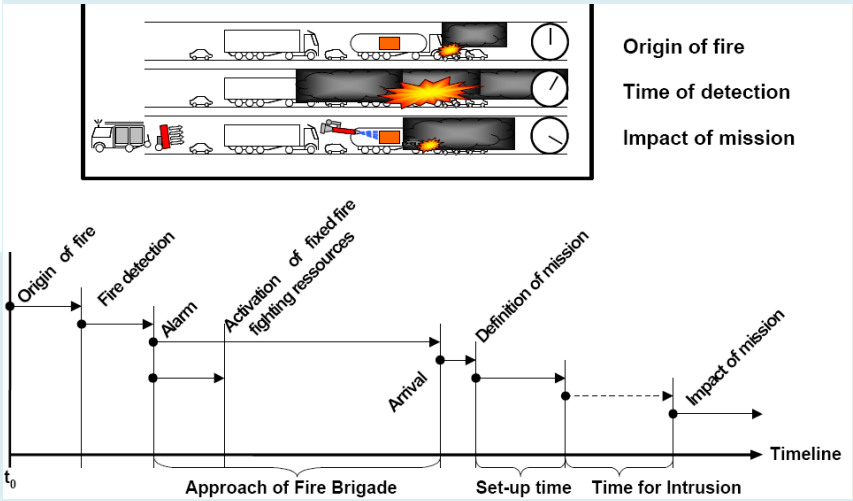
Interaction Between Tunnel Fire Suppression and Ventilation

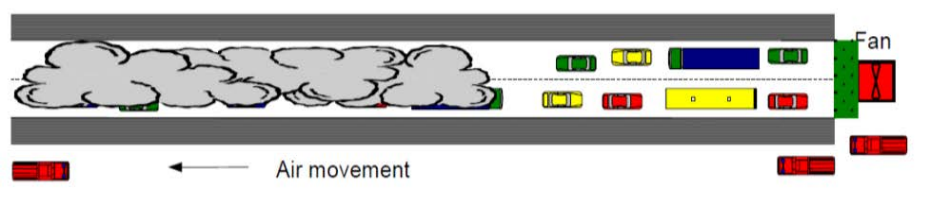
Expectations from Tunnel Ventilation and Fixed Fire Fighting Systems			
Tunnel Ventilation		**Fixed Fire Fighting Systems**	
Expected Benefits	**Expected Concerns**	**Expected benefits**	**Expected Concerns**
• Controls smoke and other gases • Provides tenable environment for evacuation, including visibility • Cools down the tunnel environment • Supports fire fighting procedures	• Increases the fire growth • Supports spreading fire further impacting other vehicles	• Slow down the fire growth, reduces fire size and overall smoke production • Prevent spreading of fire further impacting other vehicles • Cool down the tunnel environment. Cooling effect of ventilation equipment requirements • Support fire fighting operation • Protect assets	• Reduce visibility and thus negatively impact the tenable environment • Destroy stratification of hot air and smoke and may disrupt ventilation system operation • Increased humidity and its impact on tenability and fans • Produce toxic smoke due to incomplete combustion • Become slippery Hazard for evacuation

Analysis of Fixed Fire Fighting System Benefits to Extraction Ventilation					
Activation to Support Evacuation (early activation)		Activation to Support First Responders (activation after evacuation)		Activation to Support Property Protection	
Advantages	**Consideration**	**Advantages**	**Consideration**	**Advantages**	**Consideration**
• Temperature and radiation reduction	• Loss of stratification, loss of visibility and toxicity • Impact on fans and needed flow rate	• Temperature and radiation reduction	• Ventilation mode may need to be changed to longitudinal	• Beneficial on early stage	• Possible post-cooling spalling needs to be considered

Interaction Between Firefighting Operation and Tunnel Ventilation System







- Avoid backlayering of smoke:
  - higher longitudinal velocity
  - direction of airflow adaptable

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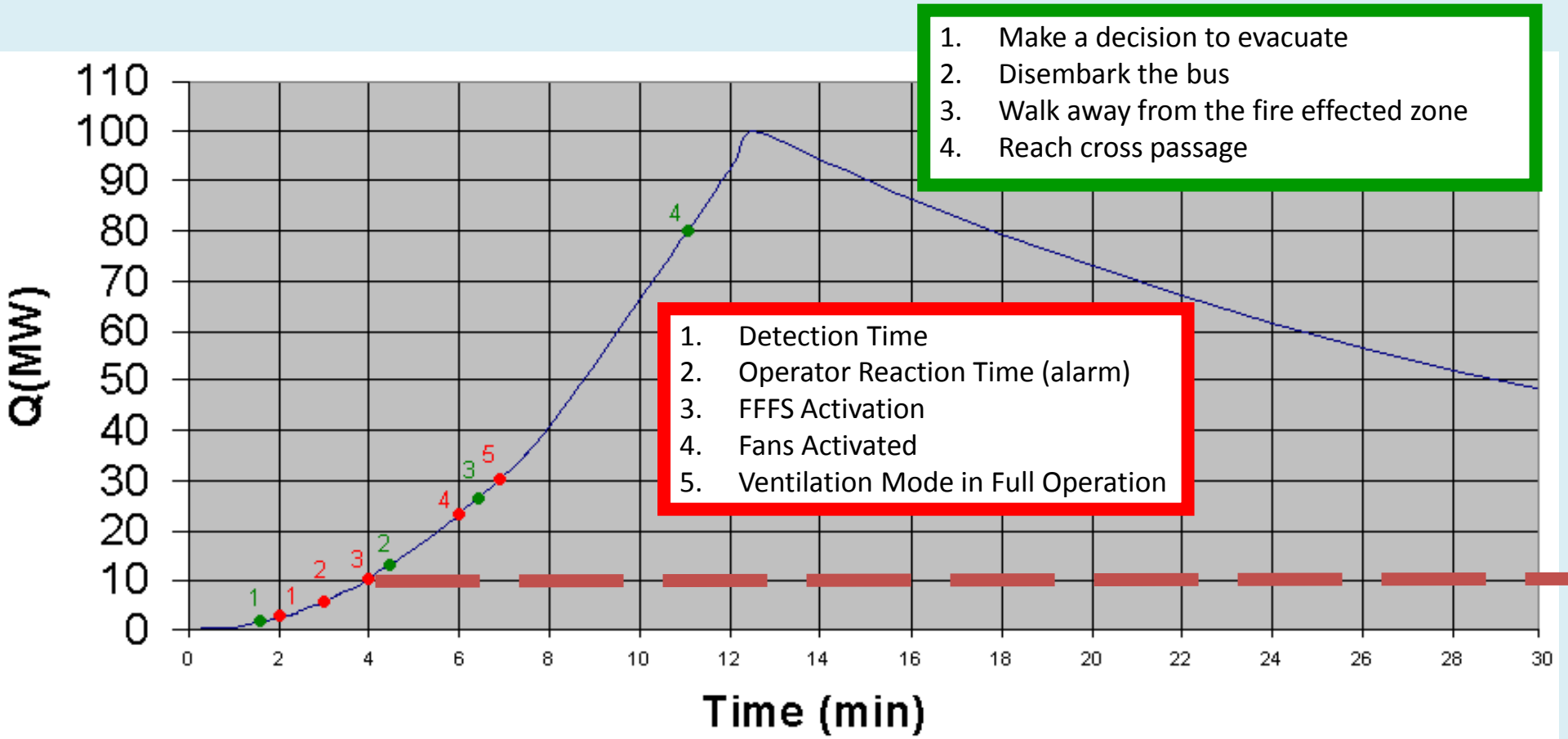
Design Heat-Egress-System Activation Time Curve



RECOMMENDATIONS TO THE OPERATORS FOR ALL FIRE SITUATIONS

- Respond in a timely manner to save lives;
- Activate fire life safety systems, such as tunnel ventilation, in accordance with the emergency response plan;
- Do not blow smoke in the direction of evacuees. Direct fresh air to support evacuation;
- Do not change the selected ventilation mode without direction from incident commander, especially during the evacuation phase.
  - Changing ventilation mode, such as reversing fans or airflow during a fire event, could spread smoke throughout the tunnel;
- Note, that over-ventilating may increase the fire size and fire growth rate and may destroy smoke stratification;
- Periodic training of tunnel operators, first responders, and their interactions is essential for a successful response.
  - Training simulators are useful tools for ventilation controls training.

Thank you!

Picture taken by Jacobs in I-90 tunnels with the permission of WSDOT

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