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

<table>
<thead>
<tr>
<th>Name</th>
<th>Email Address</th>
<th>Agency Name</th>
<th>Designation</th>
<th>Member Type</th>
</tr>
</thead>
<tbody>
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<td>Non-Voting</td>
</tr>
</tbody>
</table>
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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Jacobs Engineering
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New York, NY 10121

May, 2016

The information contained in this report was prepared as part of NCHRP Project 20-07, Task 363, National Cooperative Highway Research Program.

SPECIAL NOTE: This report IS NOT an official publication of the National Cooperative Highway Research Program, Transportation Research Board, National Research Council, or The National Academies.
1. Introduction
   – Roadway Tunnels Emergency Ventilation – Current Knowledge and Practice
   – Applicable Regulatory Standards and Guidelines
     i. US Standards and Guidelines
     ii. International Standards and Guidelines
     iii. Other publications for Emergency Ventilation Smoke Control in Roadway Tunnels

2. Road Tunnel Fires
   – Main Design Fire Parameters
   – Impact of Fire Size on Smoke Management Requirements

3. Tunnel Emergency Ventilation and Smoke Control Design Guidelines
   – Types of Road Tunnel Ventilation Systems
   – Tunnel Ventilation Systems Conditions for Application and Configurations
     i. Tunnel Length, geometry, grades
     ii. Traffic Conditions
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

- Road Tunnels Manual
- Smoke Control in Roadway Tunnels
- Current Practice for Risk Evaluation for Road Tunnels
- Approche Intégrée de la Sécurité des Tunnels Routiers
- Assessing & Improving Safety in Existing Road Tunnels: Current Practices and Recommendations
International Studies and Handbooks
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 Wärmeentzugsanlagen — Teil 3: Bestimmungen für motorische Rauch-
und Wärmeentzugsanlagen

French standard approved

by decision of the Director General of AFNOR.

Replaces the approved standard NF EN 12101-3 (classification index: S 62-300) 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.

International Standards and Guidelines
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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values Range</th>
<th>Design fire variables are a function of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Size - Maximum FHRR</td>
<td>1.5 – 300 MW [1]</td>
<td>Type of vehicle (cars, buses, HGV, Tanker; Alternative fuel)</td>
</tr>
<tr>
<td>Fire Growth Rate (slow, medium, fast, ultra fast)</td>
<td>0.002 – 0.178 kW/sec² as high as 0.331 kW/sec² 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</td>
<td>Type of cargo including bulk transport of fuel</td>
</tr>
<tr>
<td>Fire Decay Rate</td>
<td>0.042 – 0.06 (min⁻¹)</td>
<td>Fire detection system and delay in activation of FLS systems</td>
</tr>
<tr>
<td>Perimeter of Fire</td>
<td>Car – truck perimeter or pool of liquid fuel spill</td>
<td>Ventilation profile</td>
</tr>
<tr>
<td>Maximum Gas Temperature at Ceiling</td>
<td>110 °C – 1350 °C (212 °F – 2462 °F)</td>
<td>Fire suppression system</td>
</tr>
<tr>
<td>(higher with new energy carriers)</td>
<td></td>
<td>Tunnel geometry</td>
</tr>
<tr>
<td>Fire Duration</td>
<td>10 min – 6+ days</td>
<td>- tunnel width, height, cross-section, length</td>
</tr>
<tr>
<td>Smoke and Toxic Species Production Rate</td>
<td>20 – 300 m³/sec (42 – 640 kCFM)</td>
<td>- tunnel volume (available oxygen)</td>
</tr>
<tr>
<td>Radiation</td>
<td>From 0.25 to 0.40 of total heat flux up to 5125 W/m² (1625 Btu/hr/ft²)</td>
<td>- shape of tunnel, grade</td>
</tr>
<tr>
<td>Flame Length</td>
<td>Up to full tunnel height</td>
<td>- location of exits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tunnel drainage system</td>
</tr>
</tbody>
</table>
Sample Decision Making Chart on Design Fire Parameters

1. Are flammable vehicle cargo and hazardous materials allowed to travel through the tunnel?
   - Yes
   - No

2. Are a fixed fire suppression and reliable detection system considered for tunnel protection?
   - Yes
   - No

   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.
   - Yes
   - No

   Ex: Consider a quadratic fire growth rate of 187.6 W/s² with the maximum FHRR specified in NFPA 502.

3. Are heavy goods vehicles (HGV) allowed to travel through the tunnel?
   - Yes
   - No

4. Are a fixed fire suppression and reliable rapid fire detection system considered for tunnel protection?
   - Yes
   - No

   Ex: Consider a quadratic fire growth rate of 100 W/s² to maximum FHRR specified in NFPA 502.

5. Is this a bus tunnel without HGV and FLC?
   - Yes
   - No

6. Are a fixed fire suppression and reliable rapid fire detection system considered for tunnel protection?
   - Yes
   - No

   Ex: Consider a quadratic fire growth rate of 100 W/s² to maximum FHRR specified in NFPA 502.

7. Is this a special tunnel? Is this tunnel for alternative fuel vehicles?
   - Yes
   - No

Ex: Consider a quadratic fire growth rate of 100 W/s² to maximum FHRR specified in NFPA 502 with the possible reduction of FHRR based on fire detection, sprinkler activation and sprinkler system design.

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.

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

<table>
<thead>
<tr>
<th>Category</th>
<th>Tunnel Length [ft]</th>
<th>Uni-directional traffic</th>
<th>Bi-directional traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>w/HGV; w/FLC</td>
<td>w/HGV; no FLC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>w/HGV; no FLC</td>
<td>w/HGV; w/FLC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no HGV; no FLC</td>
<td>no HGV; no FLC</td>
</tr>
<tr>
<td>X</td>
<td>&lt; 300</td>
<td>No Ventilation; No Fire Suppression</td>
<td>No Ventilation; No Fire Suppression</td>
</tr>
<tr>
<td>A</td>
<td>300 - 800</td>
<td>Ventilation (suppression likely to protect structure)</td>
<td>No Fire Suppression (Ventilation questionable)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No Fire Suppression</td>
<td>Ventilation; No Fire Suppression</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ventilation; (suppression likely to protect structure)</td>
</tr>
<tr>
<td>B</td>
<td>800 - 1000</td>
<td>Ventilation (suppression likely to protect structure)</td>
<td>No Fire Suppression (Ventilation questionable)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ventilation, Fire Suppression</td>
<td>Ventilation; No Fire Suppression</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ventilation; Fire Suppression</td>
</tr>
<tr>
<td>C</td>
<td>1000 - 3280</td>
<td>Ventilation, Fire Suppression</td>
<td>No Fire Suppression</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ventilation, Fire Suppression</td>
</tr>
<tr>
<td>D</td>
<td>&gt; 3280</td>
<td>Ventilation, Fire Suppression</td>
<td>No Fire Suppression</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ventilation, Fire Suppression</td>
</tr>
</tbody>
</table>

Smoke Control in Roadway Tunnels

20
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
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   - Tunnel Ventilation Fans Utilization and Placement
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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.
Example of Design process for Consideration of Longitudinal Ventilation for the Road Tunnel Ventilation System Selection

Tunnel Flow Rate as a Function of Jet Fan Distance From Portal
Jet Fan Blowing Out of the Tunnel @ 106,000 CFM

Consider longitudinal ventilation

1. Is this a uni-directional tunnel? Yes

2. Can the traffic management system manage traffic downstream of the fire event? Yes

3. Will the tunnel NOT be used for bi-directional traffic during construction, maintenance or other events? Yes

4. Are tunnel air velocities less than (10 m/s [2000 fpm]) during normal, congested and fire emergency? 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? Yes

Consider transverse or semi-transverse exhaust, or single point extraction ventilation scheme for smoke and hot gas management or modification of longitudinal ventilation

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

Smoke Control in Roadway Tunnels
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

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

## Extraction Ventilation Systems

<table>
<thead>
<tr>
<th>TUNNEL TRAFFIC CONDITIONS</th>
<th>PRINCIPLE FOR SMOKE EXTRACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional tunnel without traffic congestion</td>
<td>• Direct airflow in direction of traffic upstream of the extraction zone to prevent or at least minimize backlayering of smoke.</td>
</tr>
<tr>
<td>Unidirectional tunnel with traffic congestion</td>
<td>• Zero longitudinal velocity at the center of the extraction zone by having airflow rates from both sides towards the extraction zone.</td>
</tr>
<tr>
<td></td>
<td>• Preserve stratification and confine the smoke to the region of the extraction zone.</td>
</tr>
<tr>
<td>Bi-directional traffic</td>
<td></td>
</tr>
</tbody>
</table>
Tunnel Ventilation Fans Utilization and Placement

- Jet Fans (Longitudinal Ventilations)
  - Saccardo Nozzle (Longitudinal Ventilation)

- Transverse Ventilation Fans
  - Centrifugal
  - Axial Fans

<table>
<thead>
<tr>
<th>Nominal FHRR, MW (MBtu/h)</th>
<th>Temperature at Central Fans, °C (°F)</th>
<th>Temperature at Jet Fans, °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 (68)</td>
<td>107 (225)</td>
<td>232 (450)</td>
</tr>
<tr>
<td>50 (170)</td>
<td>124 (255)</td>
<td>371 (700)</td>
</tr>
<tr>
<td>100 (340)</td>
<td>163 (325)</td>
<td>677 (1250)</td>
</tr>
</tbody>
</table>

FHRR = Fire heat release rate in Memorial Tunnel Tests

- Central fans located 700 ft (213 m) from fire site.
- Jet fans located 170 ft (52 m) downstream of fire site.

Distance at which Jet Fans are assumed to be destroyed by a tunnel fire

<table>
<thead>
<tr>
<th>Fire size, MW (MBtu/h)</th>
<th>Distance upstream of fire, m (ft)</th>
<th>Distance downstream of fire, m (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (17)</td>
<td>10 (32.8)</td>
<td>40 (131.2)</td>
</tr>
<tr>
<td>20 (68)</td>
<td>20 (65.6)</td>
<td>80 (262.5)</td>
</tr>
<tr>
<td>50 (171)</td>
<td>30 (98.4)</td>
<td>120 (393.7)</td>
</tr>
<tr>
<td>100 (341)</td>
<td></td>
<td></td>
</tr>
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</table>
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

<table>
<thead>
<tr>
<th>Ventilation Rate</th>
<th>Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 1 m/s</td>
<td>About 5 MW/min</td>
</tr>
<tr>
<td>About 3 m/s</td>
<td>About 15 MW/min</td>
</tr>
<tr>
<td>About 6 m/s</td>
<td>About 10 MW/min</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Detection systems</th>
<th>Fire Detection Time (s)</th>
<th>Missing Detection</th>
<th>Nuisance alarms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infra-Red fire detection</td>
<td>0 - 68</td>
<td>Once</td>
<td>No</td>
</tr>
<tr>
<td>Linear Heat Detection Type 1</td>
<td>1 - 115</td>
<td>None</td>
<td>Once</td>
</tr>
<tr>
<td>Linear Heat Detection Type 2</td>
<td>11 - 95</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td>Video flame and smoke detection Type 1</td>
<td>10 - 233</td>
<td>Yes</td>
<td>Numerous</td>
</tr>
<tr>
<td>Video flame and smoke detection Type 2</td>
<td>56 - 140</td>
<td>Yes</td>
<td>Numerous</td>
</tr>
<tr>
<td>Existing Spot Heat Detection</td>
<td>47 - 600</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
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Tunnel Fire Suppression

Water-Based Fixed Fire-Fighting System

- **Fire Suppression**: Example: Deluge system with or w/o additives such as AFFF
- **Fire Control**: Example: Deluge system
- **Volume Cooling**: Example: Water Mist system
- **Surface Cooling**: Example: Deluge or Water Mist system

Smoke Control in Roadway Tunnels
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)

<table>
<thead>
<tr>
<th>Advantages of FFFS</th>
<th>Challenges of FFFS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
</tr>
<tr>
<td>• A FFFS is designed to react on an early stage of the fire.</td>
<td>• 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.</td>
</tr>
<tr>
<td>• Takes fire under control not allowing it to further grow, or grow slowly, or extinguishing a small fire before the fire department arrives.</td>
<td>• Incomplete combustion creates smoke, gases and steam. Studies needed on critical time to activate the FFFS to protect the tunnel structures.</td>
</tr>
<tr>
<td>• 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.</td>
<td>• Creates slippery environment when water applies. May create panic when malfunctions with accidental water release.</td>
</tr>
<tr>
<td>• Protection of First Responders</td>
<td></td>
</tr>
<tr>
<td><strong>Extraction Ventilation (including single point extraction)</strong></td>
<td></td>
</tr>
<tr>
<td>• Reduced fire size.</td>
<td>• Destroys stratification of hot air, which makes ceiling extraction inefficient and evacuation difficult.</td>
</tr>
<tr>
<td>• Reduced fire duration.</td>
<td>• Increased mass of air / water mixture to move results in increased ventilation rate for extraction ventilation.</td>
</tr>
<tr>
<td>• See ‘General’ for additional information.</td>
<td></td>
</tr>
<tr>
<td><strong>Longitudinal Ventilation – Unidirectional Tunnel with Manageable Traffic</strong></td>
<td></td>
</tr>
<tr>
<td>• Reduced fire size may result in reduced ventilation rate.</td>
<td>• Increased mass of air / water mixture to move – increase ventilation rate.</td>
</tr>
<tr>
<td>• Cools environment and protect fan units from high temperature.</td>
<td>• Overcome water curtains created by the FFFS system – increase ventilation rate.</td>
</tr>
<tr>
<td>• See ‘General’ for additional information.</td>
<td>• Displacement of water particles away from the fire – increase number of FFFS zones for activation.</td>
</tr>
<tr>
<td><strong>Longitudinal Ventilation – Unidirectional Tunnel with Unmanageable Traffic or Bidirectional Tunnel</strong></td>
<td></td>
</tr>
<tr>
<td>• Protects tunnel structure.</td>
<td>• Destroys stratification, making evacuation difficult (maybe impossible) on both sides of the fire once the FFFS is activated.</td>
</tr>
</tbody>
</table>
### Interaction Between Tunnel Fire Suppression and Ventilation

#### Expectations from Tunnel Ventilation and Fixed Fire Fighting Systems

<table>
<thead>
<tr>
<th>Tunnel Ventilation</th>
<th>Fixed Fire Fighting Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected Benefits</strong></td>
<td><strong>Expected Concerns</strong></td>
</tr>
<tr>
<td>• Controls smoke and other gases</td>
<td>• Increases the fire growth</td>
</tr>
<tr>
<td>• Provides tenable environment for evacuation, including visibility</td>
<td>• Supports spreading fire further impacting other vehicles</td>
</tr>
<tr>
<td>• Cools down the tunnel environment</td>
<td>• Supports fire fighting procedures</td>
</tr>
<tr>
<td>• Supports fire fighting procedures</td>
<td>•</td>
</tr>
<tr>
<td>•</td>
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</tr>
</tbody>
</table>

#### Analysis of Fixed Fire Fighting System Benefits to Extraction Ventilation

<table>
<thead>
<tr>
<th>Activation to Support Evacuation (early activation)</th>
<th>Activation to Support First Responders (activation after evacuation)</th>
<th>Activation to Support Property Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Consideration</strong></td>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>• Temperature and radiation reduction</td>
<td>• Loss of stratification, loss of visibility and toxicity</td>
<td>• Temperature and radiation reduction</td>
</tr>
<tr>
<td></td>
<td>• Impact on fans and needed flow rate</td>
<td></td>
</tr>
</tbody>
</table>
Interaction Between Firefighting Operation and Tunnel Ventilation System

• Avoid backlayering of smoke:
  – higher longitudinal velocity
  – direction of airflow adaptable
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
Design Heat-Egress-System Activation Time Curve

1. Make a decision to evacuate
2. Disembark the bus
3. Walk away from the fire effected zone
4. Reach cross passage

1. Detection Time
2. Operator Reaction Time (alarm)
3. FFFS Activation
4. Fans Activated
5. Ventilation Mode in Full Operation
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