Appendix A17

Safety Concept

SAFETY CONCEPT

KENSINGTON EXPRESSWAY PROJECT, PIN 5512.52

December 14, 2023

PREPARED FOR

NEW YORK STATE OF OPPORTUNITY. Department of Transportation

PREPARED BY

HNTB

Content

1 Introduction and Objective

Introduction

The purpose of the NYS Route 33 Kensington Expressway Project, located in the City of Buffalo, Erie County, NY, is to reconnect the community surrounding the defined transportation corridor and improve the compatibility of the corridor with the adjacent land uses while addressing the geometric, infrastructure, and multi-modal needs within the corridor in its current location.

Figure 1: Proposed Tunnel Location

The project comprises of an approx. 4,150 ft long, 2 x 3 lane lid

Objective

Objectives of the present document are:

1. Describe important information related to the operational safety of the project.
2. Develop a comprehensive safety concept for the tunnel.
3. Provide a basis of design for tunnel systems.

2 Basics

2.1 List of Acronyms

ADT	Average Daily Traffic
AHJ	Authority Having Jurisdiction
CCTV	Closed Circuit Television
CNG	Compressed Natural Gas
EV	Electric Vehicles
FACP	Fire Alarm Control Panel
FAS	Fire Alarm System
FFFS	Fixed Fire Fighting Systems
FLC	Flammable Liquid Cargo
FLS	Fire Life Safety
HazMat	Hazardous Material
HGV	Heavy Goods Vehicle
HMI	Human Machine Interface (i.e., screen, keyboard, mouse)
ITS	Intelligent Transportation System
ITM	Inspection, Testing, Maintenance
LCC	Life Cycle Costs
LED	Light-Emitting Diode
OCC	Operations and Control Centre
PCU	Personal Car Unit
PIARC	World Road Association / Permanent International Association of Road Congresses
PLC	Programmable Logic Controller
QRA	Quantitative Risk Assessment
RAMS	Reliability, Availability, Maintainability, Safety
SCADA	Supervisory Control and Data Acquisition
TMC	Traffic Management Center
TPRD	Thermal Pressure Relief Device
UPS	Uninterruptible Power Supply
veh.	(Number of) vehicles

2.2 Reference Documents

[1] NYS Route 33, Kensington Expressway Project, Project Identification Number (PIN): 5512.52, Project Scoping Report (draft), October 2022

[2] NYSDOT Transportation Asset Management Plan, 2019

[3] NYSDOT Highway Design Manual, https://www.dot.ny.gov/divisions/engineering/design/dqab/hdm

[4] FHWA IF-05-023, Road Tunnel Design Guidelines, 2004

[5] FHWA HIF-15-005, Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual, 2015

[6] TRB NCHRP Project 20-68A , Best Practices For Roadway Tunnel Design, Construction, Maintenance, Inspection, And Operations, 2011

[7] NFPA 25, Standard for the Inspection, Testing and Maintenance of Water-Based Fire Protection Systems, 2023

[8] NFPA 70, National Electric Code, 2023

[9] NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, 2023

[10] NFPA 551, Guide for the Evaluation of Fire Risk Assessments, 2022

[11] NFPA 750, Standard on Water Mist Fire Protection Systems, 2023

[12] ANSI/IES RP-8-22, Lighting Roadway and Parking Facilities, 2022

[13] CIE 88:2004, Guide for the Lighting of Road Tunnels and Underpasses, 2nd edition

[14] PIARC (World Road Association) Road Tunnels Manual, *https://tunnelsmanual.piarc.org/en*

[15] PIARC 2008R15, Urban Road Tunnels, Recommendations to Managers and Operating Bodies for Design, Management, Operation and Maintenance

[16] PIARC 2012R23, Current Practice for Risk Evaluation for Road Tunnels

[17] PIARC 2016R01, Best Practice for Life Cycle Analysis for Tunnel Equipment

[18] PIARC 2016R03, Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations

[19] PIARC 2017R01, Design Fire Characteristics for Road Tunnels

[20] PIARC 2019R02, Road Tunnels: Vehicle Emissions and Air Demand for Ventilation

[21] PIARC 2019R03, Prevention and Mitigation of Tunnel-related Collisions

[22] PIARC 2019R05, Introduction to the RAMS Concept for Road Tunnel Operations

[23] PIARC 2022R05EN, Impact of New Propulsion Technologies on Road Tunnel Operations and Safety

[24] Ahrens M., Vehicle fires, NFPA, 2020

[25] Beard A., Carvel R. (editors), The handbook of tunnel fire safety, 2nd ed. 2011

[26] Pospisil P., Road Tunnel Ventilation, Compendium and Practical Guidelines, 2nd ed. 2020

[27] Rödiger Y., Escape Route Lighting in Road and Rail Tunnels, Swiss Tunnel Congress, 2016

2.3 Relevant Stakeholders

AHJ:	NYSDOT
Owner:	NYSDOT
Operations:	NYSDOT
Maintenance:	NYSDOT (tunnel structure and systems)
	City of Buffalo (Park)
Responding Fire Department:	Buffalo FD
Responding Police Department:	Buffalo PD

2.4 Tunnel Data

Length:	4,150 ft
Width:	2 x 50 ft
Height:	19.5 ft (16 ft clearance + 3.5 ft for equipment, typical)
	20 ft (16 ft clearance + 4 ft for jet fans)
Cross section:	1,000 sqft per tunnel roadway

2.5 Traffic Data

For traffic data considered in evaluations, see Environmental Assessment Chapters 2 (existing) and 3 (proposed).

The peak capacity for urban unidirectional tunnels is limited to approx. 2,400 veh./hr,lane, which can be exceeded only for short time intervals before the traffic flow gets congested (see [17]).

HazMat and FLC restrictions: none

https://www.fmcsa.dot.gov/regulations/hazardous-materials/national-hazardous-materials-route-registry-state

Design speed: 60 mph

Occurrence of congestions: Regular congestions on urban highway assumed

Accident and fire rates are based on available statistical data:

Fire incident rate = 4.19 fires per 100 million vehicle miles of travel (100MVM)

Accident rate = 82.02 accidents/100MVM

Accident rate is lower than the average accident rate from NYSDOT 2017-2019 data for limited-access, urban function class, divided, 6 lane highways, which is 222 accidents/100MVM, but in the same range as similar roads nationwide.

2.6 Meteorology

Meteorological boundary conditions are essential for the design of E&M tunnel systems, namely temperature data for freezing protection, and wind on portals for the tunnel ventilation assessment and design.

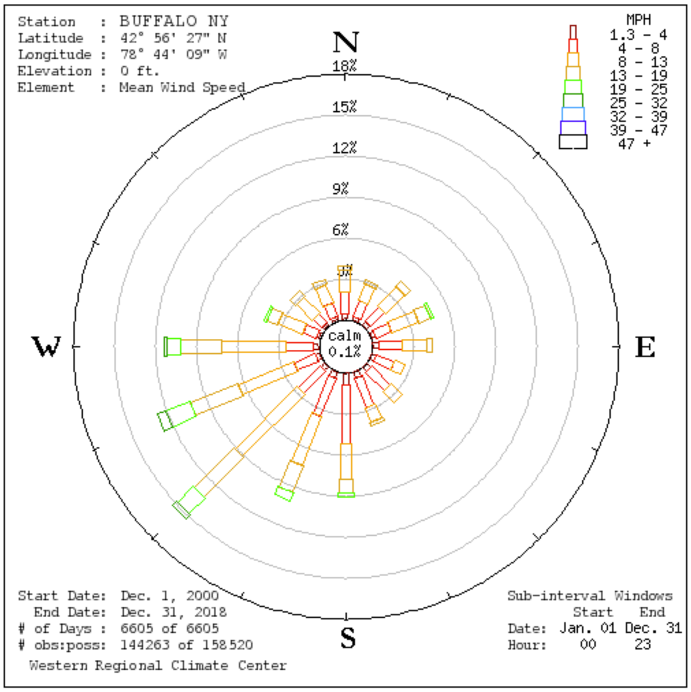

Figure 2: Wind rose for Buffalo NY

3 Hazards and Protection Goals

A specific hazard investigation is helpful to understand the impact and the risks associated with the tunnel operation. The understanding of the risks together with the protection goals are required to develop an appropriate safety concept and to derive the need and performance of fire and life safety equipment and procedures.

3.1 Hazards

General

Hazards can be decomposed into different categories, such as User Hazards, Hazards arising from the Outside Physical Environment, Hazards due to tunnel infrastructures and safety equipment malfunctions, or Hazards due to Personnel (tunnel staff and external services). However, the key hazards associated with the different kind of categories can be summarized as follows:

- Cold Incidents:
  - Collisions between vehicles
  - Vehicular (car / truck) collisions with the tunnel structure
  - Collisions with objects fallen from other vehicles or tunnel equipment
  - Toxic Gas Release
- Hot Incidents:
  - Vehicle fires (battery fires, hydrogen, gasoline)
  - Flammable liquid fire
  - Explosions (e.g., gas transport)
- Natural Disasters:
  - Flooding
  - Earthquakes
  - Freezing / snow

Collisions impose the most significant risk to drivers on roads. Generally, the collision risk in road tunnels is lower compared with open roads (see [16], [21]).

Changing light conditions distract drivers and are a main source of accidents. Therefore, the likelihood of collisions in the portal zones of typical tunnels is increased.

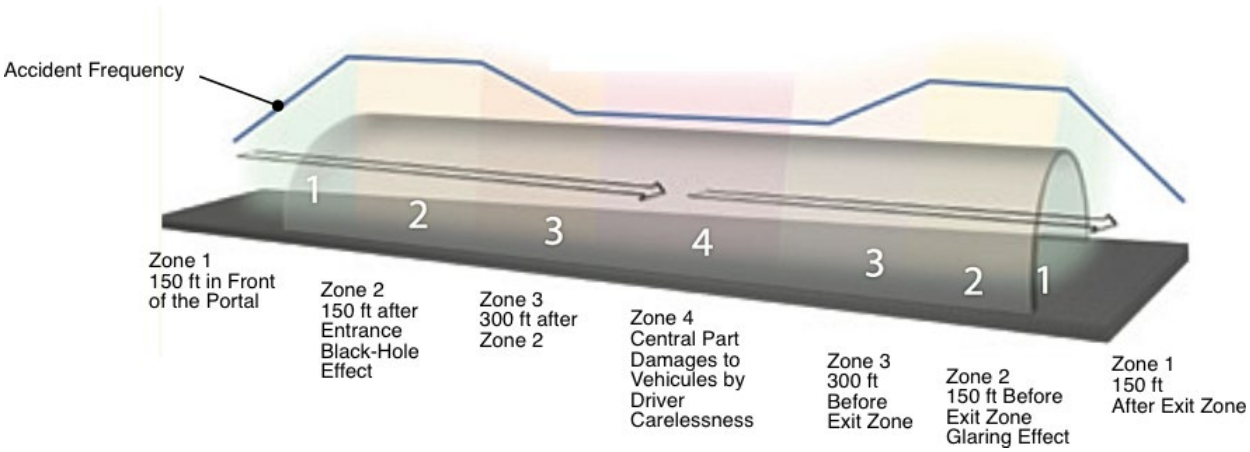

Figure 3: Tunnel Zones with Expected accident Frequency

Fires in road tunnels happen less often than collisions but may impose a serious hazard. While most vehicle fires result from technical defects, collisions are the leading cause of large fires that lead to fatalities [24]. Therefore, any safety measures reducing the collision risk also reduce the fire risk.

Hazards can be assessed by:

- Damage to health and life of drivers, maintenance personnel, and emergency service members
- Damage to vehicles
- Damage to infrastructure (road, structure, equipment)
- Damage to the environment (e.g., spillage of contaminated fire suppression water)
- Indirect economic damage, e.g., temporary disruption of highway after incidents

The probability of a collision or fire hazard on a defined road section is directly correlated to its length and traffic load. Since any traffic obstructions increase the collision and fire risk, lane closures for maintenance and construction works should be limited to the extent feasible.

In large part, risk is related to driver behavior and vehicle properties, which can only partly be influenced by safety measures on the road and tunnel infrastructure.

3.2 Safety goals and measures

The following Safety goals are proposed for the present project:

Table 1: Protection Goals for the Kensington Tunnel Project

Priority	Goal	Explanation
1.	Personal Safety	The protection of life and limb and the integrity of patrons and staff are always of utmost importance during hot and cold incidents.
	Intervention Safety	The safe escort and support during the external rescue phase by emergency forces/fire department. Especially during cold events, external rescue is of great importance and must be facilitated accordingly.
3.	Availability of the Tunnel	For the operator, it is of great interest to be able to resume operation after hot or cold incidents in the tunnel.
4.	Structural Integrity	The collapse of the tunnel during or after a hot event represents a very large loss for the operator, residents and commercial offices in the vicinity of the tunnel alignment as well as for the patrons who depend on it and the city.

3.3 Safety Measures

Safety measures are developed to ensure that protection goals for the known threats are met. To structure the planning and operation of tunnels, the four-stage safety concept below has become widely accepted.

The four-stage safety concept consists of four layers of defence: (1) prevention, (2) mitigation, (3) evacuation and (4) rescue. The highest priority and most cost-effective layer of defense is prevention. This is followed by the other priorities/layers of defense as illustrated in Figure 4.

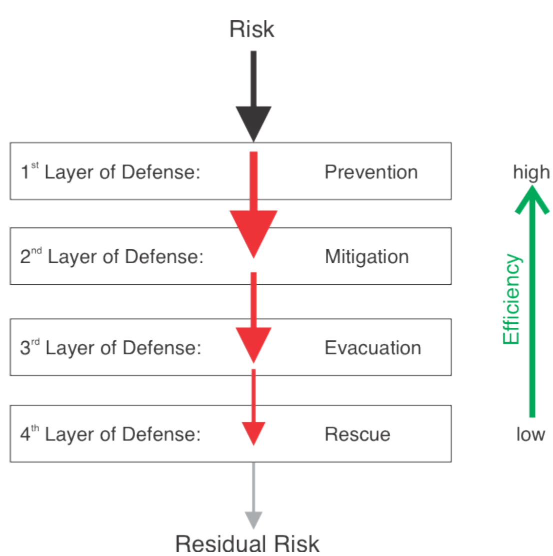

Figure 4: Priorities / Layers of a Defense of a Four-Stage Safety Concept

Aim of Prevention Measures

Prevention measures are the foundation of any safety concept and are essential for preventing emergency situations in tunnels. These measures are cost-effective and have the greatest impact on overall safety, including operation of the tunnel. They are the most important aspect to consider when developing a safety concept.

Typical prevention measures are:

- Traffic concept and road alignment providing a smooth, constant travel through the tunnel, without lane changes, as far as possible (e.g., by adequate lane & shoulder width, avoiding impact surfaces, avoiding lane merge in tunnel, etc.).
- Measures to improve driver awareness and avoid distraction.
- Speed limit, adequate to sight distance and traffic conditions, which may be enforced.
- Bright tunnel walls, dividing directions of travel and improving lighting conditions.
- Tunnel lighting providing a smooth transition between daylight and in-tunnel lighting levels.
- LED floor guidance lights assisting drivers to stay in the lane. Those also serve as wayfinding lighting in case of an incident in the tunnel (Evacuation).

Figure 5: LED Floor Guidance Lights

- Traffic management in the adjacent road network to avoid congestions in the tunnel as far as possible.
- Traffic restrictions (e.g. on Flammable Liquid Cargo).
- Intelligent traffic systems (ITS) with roadway and on-board vehicle supervision (e.g. automatic hot spot detection, tagging and tracing of hazardous goods transports), and communication between vehicles and tunnel systems.
- Careful inspection, testing and maintenance (ITM) of the roadway, tunnel structure and systems.

Aim of Mitigation Measures

Mitigation measures reduce the severity and impacts of hot or cold incidents that occur by limiting their effect.

Typical mitigation measures are:

- Signals or barriers for lane or tunnel closures in case of an incident (as required by NFPA 502, chapter 7.6.1.) with adequate length for lane changes and deviations.
- Warning signals to slow down ongoing traffic and prevent vehicles from further approaching an incident site.
- Traffic management in the adjacent road network to allow for traffic leaving the tunnel in case of an incident.
- Measures related to the structural integrity of the tunnel, e.g. FFFS.
- Tunnel ventilation (allowing for adequate sight distance and air quality inside the tunnel).

Aim of Evacuation Measures

If despite the preventive measures an incident occurs, the affected patrons move out of the danger zone to safe areas. Evacuation (self-rescue) measures are used for this purpose.

Typical evacuation measures are:

- Signage
- Tunnel ventilation (allowing for tenable conditions by smoke control)
- Emergency and guidance lights
- Egress ways and egress doors
- Public Address System

Aim of Rescue Measures

External rescue measures are used on a secondary basis and are particularly important for patrons who are trapped in vehicles or injured. Facilitating measures ensure that external rescue can begin immediately and can be carried out in a targeted manner.

Typical rescue measures are:

- Emergency responder training and exercises
- Fire apparatus and equipment of fire departments
- Means of communication for fire departments
- Firefighting equipment (standpipes, hydrants, fixed firefighting equipment, etc.)
- Access ways for the fire department

3.4 Structural Integrity

For most urban structures and overbuilt structures, a possible collapse may lead to unacceptable damage to the infrastructure above the highway, and temporary road and traffic interruption. To prevent collapse, appropriate design considering possible hazards, particularly excessive loads, natural disasters, large fires, explosions, and structural impairment must be implemented. Since the atmosphere in the present tunnel is wet and corrosive, protecting the tunnel structure and equipment from corrosion, as well as performing regular inspection, is essential.

Based on a quantitative risk analysis (QRA), a plastic deformation or even partial structural collapse may be accepted for extraordinary events with low probability (e.g., explosion of a large truck). Even then, the structural system of the tunnel must not be at risk of progressive collapse over a longer section.

3.5 Noise

Road noise has a considerable impact on the well-being and health of residents. However, it does not have any immediate effect on the safety of tunnels.

Covering the highway with a lid is an effective noise protection measure, improving the quality of life, increasing work production, and reducing healthcare costs.

4 Fire Life Safety

The present chapter focuses on tunnel fire and life safety aspects and follows the recommendations of the NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways.

4.1 Fire Sources

Most car fires result from technical defects but are usually limited in size. Many larger fires that may lead to fatalities result from collisions. Heavy Goods Vehicle (HGV) fires can lead to substantial damage, even more so when Hazardous Goods or Flammable Liquid Cargo (FLC) are involved.

Besides vehicle fires within the tunnel, burning trash or electromechanical equipment, and smoke entering the tunnel from outside, must be considered.

4.2 Code Requirements

Fire life safety design criteria are driven by the NFPA standards, namely NFPA 502 for road tunnels [9]. Requirements depend on the tunnel category. The 4,150 ft long tunnel is in category C.

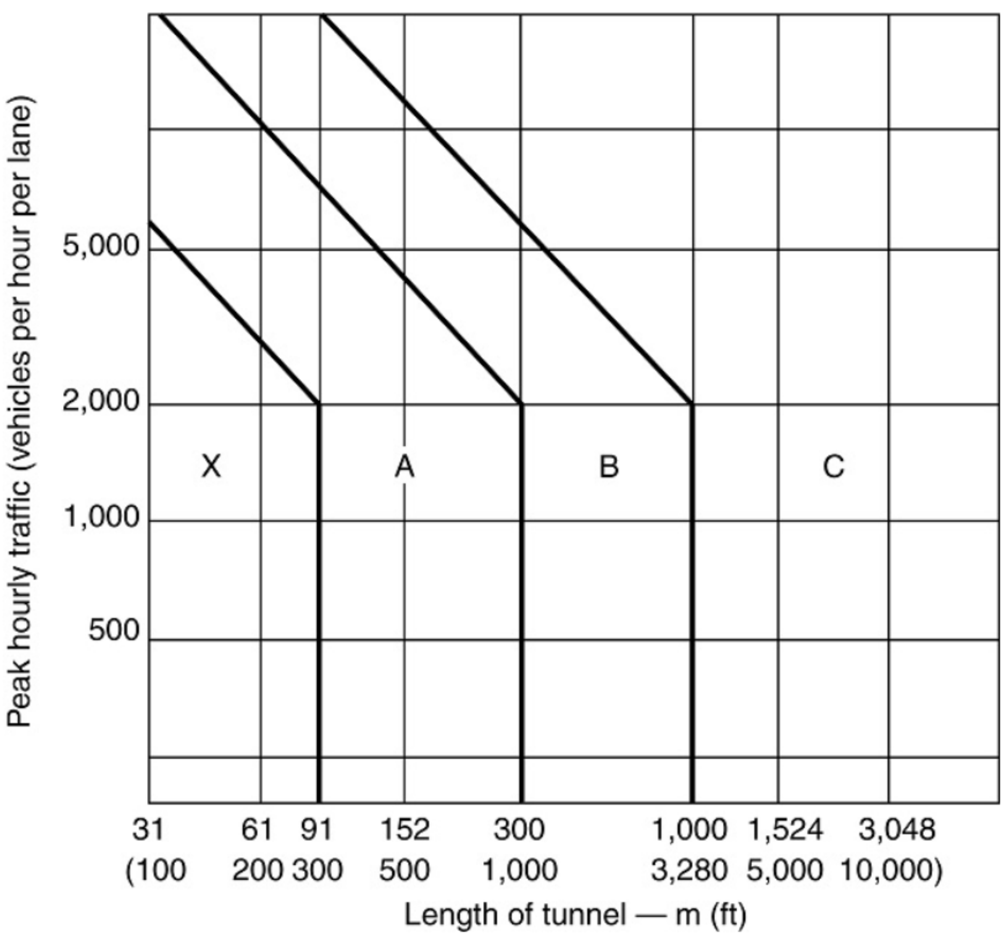

Figure 6: Tunnel Categories According to NFPA 502

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)]
Engineering Analysis					
Engineering analysis	4.3.1	MR	MR	MR	MR
Fire Protection of Structural Elements[a]					
Fire protection of structural elements	7.3	MR	MR	MR	MR
Fire Detection					
Detection, identification, and location of fire in tunnel	7.4	—	CMR	MR	MR
CCTV systems[b]	7.4.3	—	CMR	CMR	CMR
Automatic fire detection systems[b]	7.4.6.7	—	CMR	CMR	CMR
Fire alarm control panel	7.4.7	—	CMR	MR	MR
Emergency Communications Systems[c]					
Emergency communications systems	4.5/7.5	CMR	CMR	CMR	CMR
Traffic Control					
Stop traffic approaching tunnel portal	7.6.1	MR	MR	MR	MR
Stop traffic from entering tunnel's direct approaches	7.6.2	—	CMR	MR	MR
Fire Protection					
Fire apparatus[d]	7.7	—	—	—	—
Fire standpipe	7.8/10.1	—	MR	MR	MR
Water supply	7.8/10.2	—	MR	MR	MR
Fire department connections	10.3	—	MR	MR	MR
Hose connections	10.4	—	MR	MR	MR
Fire pumps[e]	10.5	—	CMR	CMR	CMR
Portable fire extinguishers	7.9	—	MR	MR	MR
Fixed water-based firefighting systems[f]	7.10/Chapter 9	—	—	CMR	CMR
Emergency ventilation system[g]	7.11/Chapter 11	—	—	CMR	MR
Tunnel drainage system[h]	7.12	—	CMR	MR	MR
Hydrocarbon detection[h]	7.12.7	—	CMR	MR	MR
Flammable and combustible environmental hazards[i]	7.15	—	CMR	CMR	CMR
Means of Egress					
Emergency egress	7.16.1.1	—	—	MR	MR
Exit identification	7.16.1.2	—	MR	MR	MR
Tenable environment	7.16.2	—	—	MR	MR
Walking surface	7.16.4	—	MR	MR	MR
Emergency exit doors	7.16.5	—	—	MR	MR
Emergency exits (includes cross-passageways)[j]	7.16.6	—	—	MR	MR
Electrical Systems[k]					
General	12.1	—	CMR	MR	MR
Emergency power	12.4	—	CMR	MR	MR
Emergency lighting	12.6	—	CMR	MR	MR
Exit signs	12.6.8	—	CMR	MR	MR
Security plan	12.7	—	CMR	MR	MR
Emergency Response Plan					
Emergency response plan	13.3	MR	MR	MR	MR

MR: Mandatory requirement (3.3.42). CMR: Conditionally mandatory requirement (3.3.42.1).

Note: The purpose of Table A.7.2 is to provide guidance for locating minimum road tunnel fire protection requirements 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 should 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 7.15.2.

[j]Emergency exit spacing must be supported by an egress analysis in accordance with 7.16.6.

[k]If required, must follow Chapter 12.

Figure 7: Minimum Road Tunnel Fire Protection Requirements According to NFPA 502

4.3 Structural Fire Protection

According to NFPA 502 chapter 5.4, 7.3 structural fire protection is required. However, long term durability under corrosive conditions and means of inspection must also be considered. The requirements can be fulfilled by the following variants:

1. Sacrificial concrete thickness on the structure and use of polymeric fibers to avoid spalling.

2. Application of mineral based fire protection panels (e.g. Promat). Those must be regularly removed for inspection of the underlying structure.
3. Steel beams can be protected by intumescent coatings, which also provide corrosion protection.
4. Water mist FFFS as described in chapter 4.9, which reduces the temperatures on the structure to the limits required by NFPA 502 chapter 7.3.4. By that, structural fire protection measures can be reduced. Life Cycle costs of the FFFS system may be lower than that of fire protection panels, considering the effort for regular removing / fixing the panels for inspection.
5. Omit structural fire protection completely based on an engineering analysis, in particular a QRA.

Furthermore, all structure and overhead equipment in the tunnel shall be capable of maintaining capacity under exposure to 842°F (450°C) for a minimum of 120 minutes as specified in NFPA 502 chapter 7.3.6.

4.4 Incident Detection

According to NFPA 502 chapter 7.4, quick and reliable incident detection is essential to release automatic, immediate reaction of active safety systems (tunnel closure, traffic management, ventilation, FFFS, etc.) and alarm tunnel operators and emergency services. Proven detection devices in road tunnels are:

- Linear Heat Detection cable
- Tunnel smoke detectors
- Acoustic incident detection
- CCTV

CCTV may be used for reliable detection of standing vehicles, pedestrians, and objects on the roadway, but currently CCTV cannot reliably detect smoke and fires, due to a high false alarm rate, and therefore needs to be confirmed by an operator.

Other specialized video detection and imaging processing systems can be used for fire detection; however, evaluation should be based on effectiveness and cost-benefit analysis.

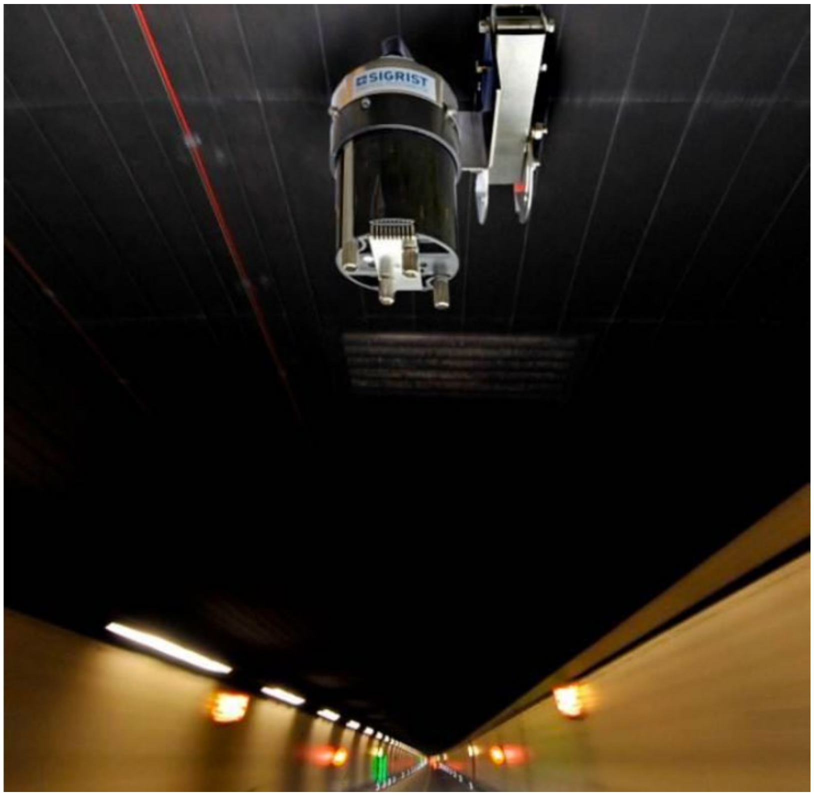

Figure 8: Linear Heat Detector and In-Tunnel Smoke Detector in Tunnel Ceiling

4.5 Emergency Communication Systems

According to NFPA 502 chapter 4.5 / 7.5, emergency communication systems are to be provided when required by the AHJ.

Reliable radio communication must be provided for emergency services.

Roadway emergency telephones are considered obsolete since motorists use mobile phones.

A Public Address System based on a Synchronized Longitudinal Announcement Speaker System (SLASS) is planned. Drivers must be instructed to leave their vehicles and escape to the closest emergency exit in case of a fire by automatic voice messages.

As a future development, modern Intelligent Transportation Systems (ITS) require adequate means of communication between vehicles and tunnel systems.

4.6 Traffic control

Traffic control is an essential safety system, not only limited to FLS according to NFPA 502 chapter 7.6.

Figure 9: Traffic Signals at Tunnel Portal

The tunnel traffic control must be integrated in the central Traffic Management Center (TMC).

Particularly in case of a fire detected in a tunnel, all tunnel portals and entry ramps on both tunnel tubes must be closed. The traffic upstream of the fire must be stopped, and vehicles downstream of a fire should be able to leave the tunnel even in case of a traffic congestion. For that, the traffic in the adjacent road network must be accordingly guided so that the traffic leaving the tunnel gets highest priority.

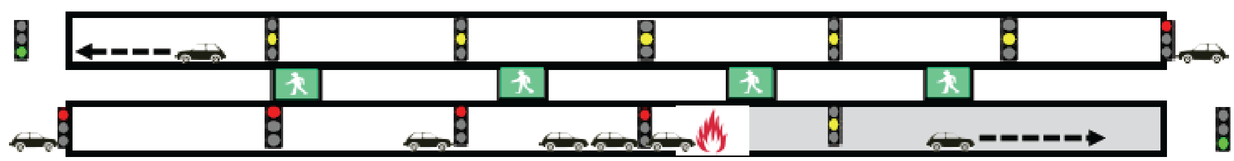

Figure 10: Schematic of Traffic Control Fire Scenario (from Road Tunnel Ventilation Compendium [26])

The tunnel traffic control must be integrated in the Buffalo Traffic Management Center (TMC).

4.7 Standpipe, Fire Hydrants and Water Supply System

According to NFPA 502 chapter 7.8 / 10 standpipes, water supply and fire department & hose connections must be provided. Fire hydrants should be located at each tunnel portal according to water utility availability and fire department requirements. Hose connections in the tunnel should be placed at intervals of not more than 275 ft, considering a max. hose length of 150 ft.

Due to climatic conditions in the project area, freezing protection measures have to be applied to water supply and standpipes.

The water supply system must be designed to provide the flow necessary for a design fire event inside the tunnel. Fire-fighting activities may include simultaneous use of the fixed fire-fighting system, tunnel standpipe and/or fire hydrants outside the portals. If the municipal water supply cannot meet the flow demand, water storage and fire pump may be needed.

For the water capacity, as well as for the drainage storage, it must be considered that Electric Vehicle (EV) fires may require extraordinary volume of extinguishing water, more than specified in the actual code requirements, or minimum 750 gpm for 1 hour as per NFPA 502 chapter 10.2 and NFPA 14 chapter 7.10.

4.8 Portable Fire Extinguishers

According to NFPA 502 chapter 7.9, portable fire extinguishers are required along the roadway in approved wall cabinets or niches at intervals of not more than 300 ft. Since the hose connection requirement is more restrictive, fire extinguishers will be foreseen at the same locations as the hose connections.

4.9 Fixed Fire Fighting Systems (FFFS)

According to NFPA 502 chapter 7.10. / 9 and Annex E.

Considering the high traffic load and possibility of FLC, HGV and Alternative Fuel fires, we propose to equip the lid with a high-pressure water mist FFFS, as an alternative or in addition to structural fire protection measures, with the following arguments:

- Water mist FFFS limit fire growth, temperatures and smoke production for all kind of fires, even when shielded under a roof or tarpaulin, or within a vehicle compartment.
- Flammable liquid fires can be mostly extinguished by water mist.
- By that, the fire impact on the structure can be significantly reduced. Temperatures on the structure can be limited to the thresholds as required by NFPA 502 chapter 7.3.4.
- The tunnel can be quickly reopened for traffic even after large fire incidents, which otherwise would require roadway closures for longer periods for refurbishment works.
- FFFS reduce the amount of smoke exiting the tunnel, which otherwise would seriously affect the environment around the tunnel.
- A water mist system requires substantially less amount of water than a deluge system.

Drawbacks to be considered:

- FFFS require substantial costs for investment, maintenance, and regular testing.
- A water mist system requires high pressure pumps and adequate redundant power supply.
- High reliability and redundancy of FFFS, equipment control and power supply is required.
- FFFS may cause traffic accidents in case of inadvertent release from false alarm, equipment failure and/or human error. Therefore, a positive alarm sequence must be incorporated with TMC staff monitoring.
- Freezing protection measures are required.

Figure 11: Test Activation of Water Mist FFFS in a Road Tunnel

Considerations for mist sprinkler design include application rate, capacity of municipal water supply, duration of fire event, mist nozzle layout, mist/fire zone layout, quantity of active zones, fire detection response time, mist sprinkler activation time, equipment room layout to accommodate maintenance and removal. A break tank may be required.

Considerations about FFFS should take into account accessibility, response times and means of fire-fighting of local Fire Brigades, as described in the emergency response plan.

For the preliminary design, a water mist FFFS is assumed. The usefulness of a FFFS in comparison to structural fire protection measures can be justified based on a monetized risk assessment, with an analysis of life cycle costs (LCC, including investment, operation, maintenance, refurbishment), taking into account application, durability, maintenance, repairability and inspection. Those costs would be compared to the expected benefit of particular safety measures, namely repair costs and economic damage due to closure of the highway for refurbishment after a large HGV fire, and the probability of such an incident.

4.10 Emergency Ventilation

According to NFPA 502 chapter 7.11. / 11, for tunnels longer than 3,280 ft, a tunnel ventilation system is required, which is described in Chapter 5.

4.11 Dividing Walls

Dividing walls between tunnel tubes serve to separate traffic and airflows, particularly in case of a fire to prevent smoke recirculation into the non-incident tube before the fire is detected, traffic is stopped and the fire ventilation becomes effective. At both portals of the Kensington Expressway lid, an extension of the central wall over a length of 100 ft, at tunnel clearance height, is required.

Figure 12: Dividing Wall at Tunnel Portal

4.12 Drainage System

According to NFPA 502 chapter 7.12.

The drainage system, constructed of noncombustible materials, must be designed for the spill of a FLC transport tank and for fire extinguishing water. The drainage in the tunnel should be preferably in the form of a slotted channel on the right side of the roadway, to minimize the possible area of spilled flammable liquid, connected to comparted collectors in regular distances.

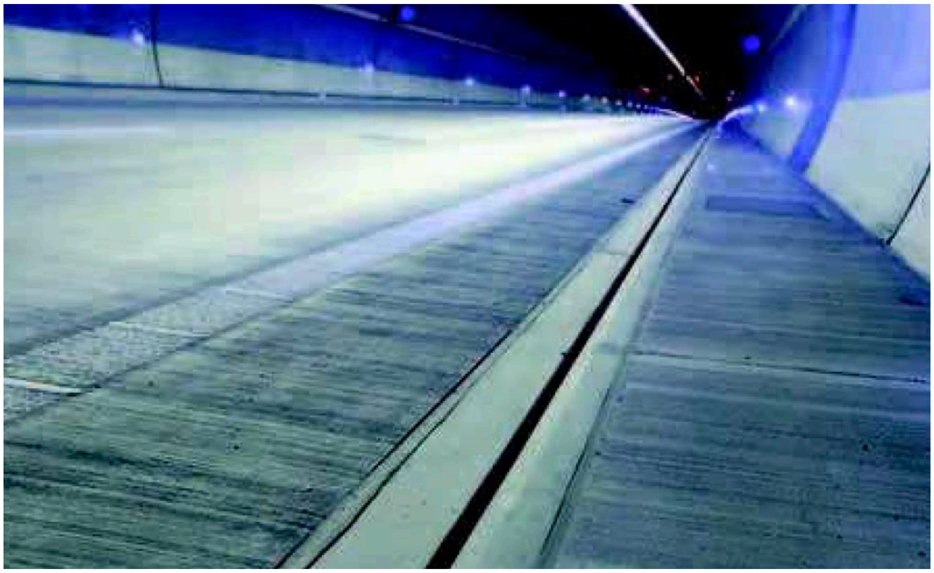

Figure 13 Slotted Channel for Drainage

All drainage water must be collected into a retention tank, adequately sized to contain extinguishing water and Hazmat / FLC. Extinguishing water may be highly toxic and impose an environmental hazard that is likely to require decontamination of drainage piping and tanks.

Hydrocarbon detection is required for storage tanks and pump stations, and a tank room ventilation system to prevent explosive concentrations. Nevertheless, electrical and mechanical equipment, namely the pumps, must be able to safely operate within an explosive environment. Due to climatic conditions in the project area, freezing protection measures have to be applied.

4.13 Control of Hazardous Materials / Environmental Hazards

According to NFPA 502 chapter 7.14 / 7.15 / 14, measures to reduce the risks resulting from hazardous and flammable materials may be evaluated, including:

- Providing escort vehicles for Hazmat and FLC transports ensures an adequate safety distance to the other traffic.
- Equipping FLC and Hazmat transports with electronic tags can be detected by tracking systems, automatically warning adjacent traffic, and informing tunnel operators and emergency responders in case of an incident.
- Implementing automatic vehicle fault detection and communication with ITS.

4.14 Emergency Exits

According to NFPA 502 chapter 7.16, the permissible distance between emergency exits is max. 1000 ft (305 m). Main exits are the tunnel portals. In tunnels with high probability of congestion, where people may be located on both sides of a fire, shorter distances between emergency exits should be applied. When tunnel roadway cells are separated only by a dividing wall, emergency exits to the non-incident tunnel can be realized at little cost as cross passages. Those can also be used for emergency services ingress.

It is proposed to provide the emergency exits at the same locations as the fire niches with hose connections and fire extinguishers. Therefore, 14 emergency exits are foreseen in the dividing wall to the adjacent tunnel tube in distances of 277 ft.

Each cross passage is equipped with a fire-resistant sliding door with minimum clear width of at least 4 ft (NYSDOT Highway Design Manual 2.7.5.9). Exit doors must easily be opened under all conditions, not exceeding the door opening force 222 N / 50 lbs according to NFPA 502, chapter 7.16.5.6. T.

Emergency exits should be appropriately signalized with exit signs according to NFPA 502, chapter 12.6.8, being visible even in a smoke-filled environment.

4.15 Power Supply

According to NFPA 502 chapter 12 / NFPA 70, in the event of failure of the normal power supply to the tunnel, emergency power shall be available. Utility connections to two independent power distribution grid substations are provided according to NFPA 70, chapter 700.12 (D).

A UPS according to NFPA 70, chapter 700.12 (B) will be provided to ensure that all safety relevant control systems, FAS, emergency lighting and wayfinding lighting are never interrupted longer than 0.5 s according to NFPA 502.

4.16 Alternative Fuels

Transformation of road traffic to non-fossil fuels improves sustainability, but brings new challenges to Fire Life Safety systems, as mentioned in NFPA 502 annex G.

- Battery fires in EVs cannot be extinguished with directed water sprays, only controlled and cooled, and may burn for a long time. Large amounts of fire extinguishing / cooling water are required, which is contaminated and must be contained and disposed of as a Hazardous Material.
- CNG and Hydrogen tanks may lead to fire jets when exposure to heat initiates forced pressure relief from fuel tank temperature pressure relief device (TPRD).
- Released CNG and Hydrogen may accumulate and explode when ignited.

Such hazards must be prevented or mitigated by appropriate safety measures, which are subject to ongoing development.

5 Tunnel Ventilation

5.1 Normal Operation

Due to low vehicle emissions, the natural ventilation induced by the vehicle piston effect provides an adequate in-tunnel air quality in road tunnels with unidirectional traffic, more so when considering the increasing percentage of EVs. A mechanical ventilation system is not required for normal operation, except for extraordinary situations, e.g. long-lasting congested traffic with idling engines and unfavorable meteorological conditions.

5.2 Fire Ventilation

The application of a mechanical ventilation in a tunnel does not necessarily increase the safety level. Ventilation may even deteriorate conditions in case of a tunnel fire when operated inappropriately. Most fatalities in road tunnel fires were caused by smoke spread induced by the tunnel ventilation system [25].

Objectives for fire ventilation in the incident tunnel are specified in NFPA 502 chapters 11.2.3 (bidirectional traffic where motorists can be on both sides of the fire site) and 11.2.4 (unidirectional traffic where motorists are likely to be located upstream of the fire site). NFPA does not explicitly refer to urban tunnels with unidirectional traffic with high probability of congestions, even when those tunnels represent the most important share of road tunnels in the US. In such tunnels, motorists can be on both sides of the fire site. Fire ventilation goals in such urban highway tunnels are:

- Control smoke spread in the incident tunnel.
- Prevent smoke spread to the non-incident tunnel at the portal.
- Prevent smoke spread to the non-incident tunnel through open cross passages.

As outlined in the Road Tunnel Ventilation Compendium [26], the following principles apply for the design of ventilation systems and their operation:

- Flow reversal in the incident tube must be avoided.
- Longitudinal air flow in the incident tube shall be directed but kept at low magnitudes to enable smoke stratification. For that, a flow control based on precise and reliable in-tunnel flow measurement is required.
- Jet fan operation close to a fire would immediately smoke up the whole cross section and enforce an additional smoke spread, endangering people in the tunnel. Therefore, fans in the vicinity of the fire location must be switched off and are not available.
- For the design, the non-availability of fans close to the fire must be considered by providing additional fans at different locations.

- The flow in the non-incident tube must be reversed quickly against the traffic direction, to avoid smoke spread into the non-incident tube at the portal.
- In the non-incident tube, an overpressure must be generated to avoid smoke spread into the non-incident tube through open cross passages.
- Minimal distances are required for momentum transfer from impulse fans and for adequate flow measurement.

Safety goals, especially flow reversal in the non-incident tube to prevent smoke entry at the portal, cannot be achieved as long as the traffic is moving. Ongoing traffic in the incident tube provides the desired ventilation direction. However, moving cars endanger escaping people, and vehicles downstream of the fire may be entrapped in the smoke. Moving traffic in the non-incident tube would draw in the smoke exiting from the incident tube portal. Therefore, stopping the traffic in both tunnel tubes after a confirmed fire alarm is essential.

When the Fire Department arrives on site, they are likely to find stable (pre-defined) flow conditions. Manual overriding of ventilation operation to force a change of flow conditions would cost time and is likely to lead to additional risks.

Figure 14: Firefighting an HGV Fire in a Highway Tunnel under Controlled Flow Conditions

6 Control and Operation

Operation of each tunnel system (lighting, signaling, ventilation etc.) in normal and emergency modes must be fully automatic, with manual override capability by operators. Adequate training and regular emergency rehearsals of those operators is essential.

In case of an incident (e.g. standing vehicle, collision, fire), automatic lane or tunnel closures must be initiated, after a positive alarm sequence that allows operators to react in case of a false alarm. For the automatic release of FFFS in case of a fire, a positive alarm sequence must also be implemented, because an erroneous release may lead to accidents.

Emergency modes of other safety systems where erroneous release would have no detrimental effect on traffic operation, namely emergency lighting, exit signage and fire ventilation, must be switched on immediately after automatic processing of the incident detection signal, without need for manual confirmation.

The following control system structure is foreseen:

- Each subsystem (e.g., ventilation, lighting, signaling, FFFS, etc.) consisting of instruments, actuators and PLCs works autonomously.
- Instruments, actuators, and PLCs along the tunnel and in technical rooms are connected to a communication ring. In case of an interruption of a communication line the communication is automatically switched to the alternate path.
- All subsystems are connected to the FAS and SCADA with HMI in technical rooms at the TMC.
- FAS has a higher priority than SCADA.
- Signal processing (time averaging, plausibility checks etc.) is implemented on the PLC.
- The failure of single components and subsystems is automatically compensated by fallback modes as far as reasonably practicable.

The control systems, FAS and SCADA are to be protected by a comprehensive Cybersecurity concept.

7 Inspection, Testing and Maintenance

Inspection, Testing and Maintenance (ITM) of Tunnel Systems must be integrated in an Asset Management Plan (AMP). Specific life cycles of different structures, systems and equipment are the basis for a life cycle maintenance and refurbishment program.

Structural inspection cycles are usually 24 months, and equipment ITM cycles 12 months. Specific NFPA standards may require shorter intervals, e.g. weekly testing of fire pumps according to NFPA 25.

Since any traffic obstructions increase the collision and fire risk, lane closures for intervention, maintenance and construction works should be limited as much as possible, and appropriate temporary risk reduction measures implemented.

High quality and reliability of tunnel equipment is essential, considering the harsh environmental conditions and wet and corrosive atmosphere in the tunnel. All safety relevant equipment and systems must be thoroughly tested out prior to acceptance.

It is proposed to work out realistic hot smoke tests under different boundary conditions to test FLS systems prior to the tunnel opening and later for reassessment after several years of operation.

Figure 15: Hot smoke Test in a Road Tunnel

8 Emergency Response Plan

An emergency response plan according to NFPA 502 chapter 4.4, 13 must be prepared in close collaboration with emergency services, Fire Department, tunnel operators and other stakeholders from the early project stage and may have an impact on the safety concept.

Accessibility, response times and means of firefighting are considered for the concept and design of FLS systems.

For emergency services, the empty non-incident tunnel is the fastest and safest means of access to approach close to the fire location and then by cross passages into the incident tunnel to the fire site, since the incident tunnel may be impaired by standing vehicles upstream and smoke downstream. They will find fire hose connections opposite to the emergency exits.

Approaching emergency services must be aware of the presence of people in both tunnel tubes.

Regular training and exercises of emergency responders shall be conducted at least twice a year according to NFPA 502 chapter 13.8.4.

9 Construction Program

A detailed safety concept has to be developed for each construction phase to maintain an adequate level of safety during the whole construction process, considering lane closures and traffic restrictions.

Additional traffic management measures are required to minimize risks, e.g., preferably always operate roadways in unidirectional traffic and minimize times with bidirectional traffic, temporary restriction of Hazardous Goods / FLC, to be allowed only during defined hours.

Tunnel systems will be successively installed, commissioned, and tested in segments with progressing construction works, which will increase the necessary effort.