SAFETY CHALLENGES OF HIGHWAY LIDS IN THE US

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ABSTRACT

Covering highways with lids creates space for recreation and urban development, reduces noise and pollution, and improves traffic safety, among other benefits. Urban highways are characterized by large traffic numbers on multiple lanes with regular congestion. While actual road tunnel safety knowledge is mostly derived from European tunnels with two or three lanes per tunnel cell, there are a few examples of modern urban highway tunnels with many lanes in each direction. Local driving habits and codes need to be considered alongside the laws and provisions in the US.

Basis of design is a safety concept, describing safety systems and equipment in order of their effectiveness, prioritizing preventive measures. An Engineering Analysis for approval by the Authority Having Jurisdiction (AHJ) is required by the governing fire safety code NFPA 502. For that, we propose a Quantitative Risk Analysis (QRA), focusing on accident risks based on statistical data, and on fire risk based on simulations of smoke spread and egress for different scenarios under varying initial and boundary conditions. Statistical data about accidents and vehicles fires are available from the vast US road network. Tunnel specific European data and adapted to conditions in US high-way lids which differ from European tunnels. The appropriate simulation of different traffic scenarios is essential to understand the application of measures such as detection and traffic control, emergency exits, mechanical ventilation and Fixed Fire Fighting Systems. This paper describes a holistic approach to tunnel safety by providing a methodology for developing safety concepts and QRA with focus on tunnel ventilation aspects.

Keywords: Highway Lids, Tunnel Safety & Ventilation, Risk Analysis

1. INTRODUCTION

In many countries, highways have been built through cities, disconnecting urban centers and neighborhoods. Covering such highways with lids creates space for recreation and urban development, reduces noise and pollution, and improves traffic safety, among other benefits. Urban highways in the US are characterized by unidirectional traffic on multiple lanes with regular congestions, and large cross sections. Actual road tunnel safety knowledge is mostly derived from European tunnels with two or three lanes per tunnel cell, but there are few urban highway tunnels with many lanes in each direction.

Key differences between Europe and the US to be considered are:

- Legal framework
- Driving habits
- Operational experience

2. US SPECIFIC CONDITIONS

2.1. Legal Framework

Most European countries with extensive tunnel experience have a framework of road tunnel standards, providing coordinated and detailed requirements for the concept, design, operation and quality assurance of road tunnel structures and systems (e.g., [9]).

Details of the legal framework in the US are not subject of this paper, but it should be mentioned that in the US, road safety requirements are based on federal, state and AASHTO guidelines [3], and tunnel safety systems are determined by various guidelines e.g., the ANSI/IES guideline RP-8 [4] for tunnel lighting, the NFPA 502 standard [1] for fire safety measures including fire ventilation, the ANSI/ASHRAE Standard 217 [5] for operational (non-fire) ventilation, and the FHWA TOMIE manual [6] for operation and maintenance.

A tunnel project in the US must be approved by the local Authority Having Jurisdiction (AHJ), which is often the Fire Marshall. This AHJ usually refer to codes such as NFPA 502 (see [1]), which formulate performance-based requirements referring to an 'engineering analysis.' The specific methodology for this analysis is not detailed prescriptively, which can lead to different interpretations in practice.

Often, AHJ follow building codes for fire life safety, arguing that a road tunnel is a building. Consequently, tunnel systems in the US are sometimes planned by designers who apply a 'Fire Life Safety' approach derived from building codes. This approach may not always fully address the specific conditions unique to tunnel environments, in particular the vehicular traffic and resulting longitudinal airflow.

In cases of uncertainty, there may be a preference for a technical solution perceived as the most conservative, potentially placing less emphasis on cost-benefit considerations or long-term operational issues. That is explained in particular for the example of tunnel ventilation (section 5).

2.2. Driving Habits

In contrast to the conservative approach often seen in tunnel system design, road traffic fatality rates in the US are statistically higher than in many comparable European countries. E.g., in 2022, the road fatality rate per billion km driven was 8.2 in the US, and 4.6 in Germany (a country without speed limit on highways). The road traffic fatality rate per inhabitant is even approx. 4x higher than in Europe considering that Americans on average drive more.

Different driving behaviors may be a contributing factor. For example, the observance and enforcement of speed limits in the US may be less strict. On multi lane highways, weaving and sudden braking are major causes of collisions. This needs to be considered for road tunnel risk assessment and operational measures, in particular traffic management.

2.3. Operational Experience

The first US automobile tunnels were the Liberty tunnel in Pittsburgh opened in 1924 and the Holland tunnel under the Hudson river between New York and New Jersey in 1927.

Transversal tunnel ventilation for dilution of vehicle emissions was developed by the Pittsburgh Bureau of Mines. However, in the following decades, only few, mostly short road tunnels were built. Today, there are approx. 185 road tunnels with a length exceeding 300 m (1000 ft) in the US, according to the FHWA National Tunnel Inventory database (NTI).

In contrast, in Europe, there are over 4000 road tunnels with lengths exceeding 300 m, and much longer tunnels. After large fire incidents in the 1990s, European road tunnel safety has been substantially improved, and there is extensive operational experience with modern road tunnels and their safety systems.

Urban highway lids in the US were built since the 1970s, but most of the existing or actually planned or constructed lids are very short, with lengths rarely exceeding 500 m. On the other side, US highway lid cross sections are mostly larger than in European tunnels.

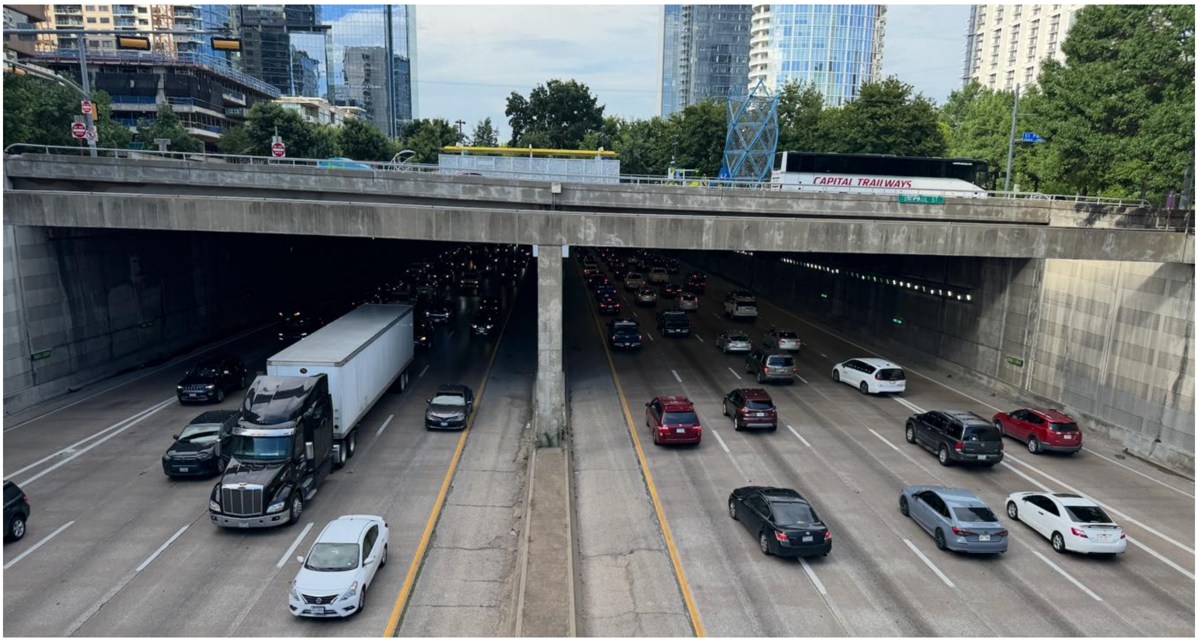

Figure 1: Klyde Warren Park, Dallas TX, 366 m long, opened 2012 (photo by author)

3. SAFETY CONCEPT

3.1. Overview

A holistic safety concept serves as the design basis for road and structural measures, systems and equipment, and has been described in other publications (e.g., [23]). Hazards are evaluated and assessed, safety goals are defined, and safety measures are ranked by effectiveness to prioritize prevention while complying with US codes and guidelines that focus on fire and life safety. The following discussion focuses on the most significant hazards in road tunnels and highway lids: collisions and fires. Other hazards, such as natural disasters or structural collapse, must also be considered within the safety concept but are beyond the scope of this paper.

3.2. Hazards: Collisions

Collisions impose the most significant risk to drivers on roads. The risk is largely related to driver behavior and vehicle properties.

Generally, there is an increased likelihood of collisions in tunnel portal zones, same as under wide bridges, due to changing light conditions. In contrast, the interior of tunnels provides safe, uniform conditions. Drivers are shielded from changing light, unfavorable environmental conditions such as rain, snow and ice, and tunnels prevent collisions by inhibiting access to pedestrians and animals. Therefore, the collision risk in long road tunnels is lower compared to open roads.

3.3. Hazards: Fires

Fires on roads happen far less often than collisions. According to US NHTSA and NFPA data ([17], [18], [19]), and the PIARC report [15]:

- Approx. 70 - 80% of vehicle fires result from technical defects (mechanical, electrical), 10 - 20% from collisions.
- In 80 – 90% of fires "there is neither personal injury nor damage to property", that means most vehicle fires are insignificant.
- Approx. 0.3% of collisions result in fires.
- While collisions are not the primary cause of fires overall, they are the leading cause of particularly large fires that can result in fatalities and significant structural damage.
- Therefore, any safety measures that reduce the collision risk also reduce the fire risk.

4. SAFETY MEASURES

4.1. Prevention

Hazard prevention, primarily concerning collisions and fires, is the highest priority. The following prevention measures apply both to open roads [7] and tunnels:

- Driver education.
- Well maintained vehicles in good condition with on-board safety systems (e.g., driver assistance systems).
- Traffic concept and road alignment providing a smooth, constant travel through the tunnel as far as possible (e.g., by adequate lane & shoulder width, avoiding impact surfaces, avoiding lane merges in tunnels, avoid weaving, etc.).
- Measures to improve driver awareness and avoid distraction.
- Speed limit, adequate to sight distance and traffic conditions, that may be enforced.
- Traffic management, avoiding congestions.
- Traffic restrictions (permanent or temporary, e.g., on hazardous goods).

Tunnel specific prevention measures [16] are:

- Bright tunnel walls, shielding drivers from distraction, separating roadway directions, and serving as fire compartmentalization.
- Wide shoulders.
- Tunnel lighting, which is directly related to the permitted speed and sight distance. Appropriately designed and controlled lighting is especially important to reduce the collision risk in the portal zones.
- Floor guidance lights reduce the probability of accidents and serve as wayfinding lighting for egressing motorists in case of a fire.
- Mechanical ventilation to ensure acceptable air quality and visibility
  (see section 5)
- Regular inspection and maintenance of structure, systems, and equipment.

Since any traffic obstructions increase the collision and fire risk, lane closures for maintenance and construction works should be limited as far as possible.

4.2. Mitigation

Mitigation measures reduce the immediate impact of an incident when prevention failed.

- Fast incident detection, in particular:
  - Acoustic Detection System (ADS)
  - CCTV camera system with Automatic Incident Detection
  - Smoke detection / visibility measurement
  - Fire detection (Linear Heat Detection system)

  Reliability of detection is essential, because false alarms may have negative effects.
- Signals and barriers for lane or tunnel closures in case of an incident with adequate length for lane changes and deviations.
- Signals inside long tunnels, to prevent vehicles from approaching the incident site further.
- Traffic management in the adjacent road network, to allow for traffic leaving the tunnel in case of an incident.
- Fixed, automatic Fire Suppression System (FFFS).
- Drainage.

4.3. Evacuation

Evacuation measures facilitate the safe egress of tunnel occupants from the hazard zone to a designated place of safety.

- Wide shoulders to provide safe evacuation path beside active traffic lanes.
- Emergency exits in short distances, equipped with appropriate doors and signage.
- Emergency lighting and floor guidance lights.
- Public Addressing / Voice Alarm System (PA/VA).
- Mechanical ventilation / smoke control (see section 5).

4.4. Rescue

Rescue measures facilitate emergency service operations in rescuing motorists and suppressing fires.

- Emergency Response Plan.
- Emergency responder access routes.
- Staging areas at portals.
- Means of communication.
- Standpipes with FD connections.
- Staging areas at portals.
- Rescue equipment.
- Regular emergency responder training & exercises.

Those measures protect in first order life and health. Asset protection measures, such as structural fire protection, are treated separately.

5. TUNNEL VENTILATION

5.1. Basic Considerations

Tunnel ventilation is a key feature that can either mitigate or aggravate smoke spread in a tunnel, which affects tenable conditions for evacuation of motorists and access of first responders. For highway tunnels with unidirectional traffic, longitudinal ventilation with impulse fans (jet fans or nozzles) is the mechanical ventilation system of choice. Additional concentrated smoke exhaust is required in some European countries for urban highway tunnels with high probability of congestions and blocked vehicles, but substantially increases costs and can bring additional risks (see Compendium [23]). Transversal ventilation systems, as applied until a few decades ago for the dilution of high vehicles emissions, are considered obsolete nowadays.

The key questions are, when does a mechanical ventilation make sense, and how should it be operated? As explained in the Compendium [23], in short tunnels, the number of motorists potentially exposed to smoke is low, escape routes to the portals are short, and short tunnels would be smoked-up across a large part before the ventilation could even react.

5.2. Comparison Europe – US

Referring to highway lids with unidirectional traffic, key differences between actual tunnel ventilation requirements in Europe and the US are as follows:

- According to the EU directive [8], which determines minimum requirements, mechanical tunnel ventilation is not required for tunnels under 500 m length. That may vary in country specific guidelines. E.g., in Switzerland, the minimal length for ventilation requirement in unidirectional traffic tunnels is 600 – 800 m [9]. Switzerland has only approx. 0.4% of the area of the US, but almost twice as many road tunnels exceeding 300 m length, and much longer tunnels.
- Currently in the US there are some very short highway lids with lengths under 500 m that are equipped or planned with a mechanical ventilation. The design basis may focus on a specific hypothetical scenario where ventilation is beneficial (see Figure 4). This might not fully account for dynamic effects, such as traffic-induced airflow, or scenarios where mechanical ventilation could be detrimental (see Figure 6). In practice, operational records show that some ventilation systems are not activated at all, even during fire incidents, while still requiring regular testing and maintenance.

Figure 2: Central 70 cover, Denver, CO, 307 m long, opened 2022 (photo by author)

- In Europe, ventilation requirements for urban highway tunnels with high probabilities of congestions are similar as for bidirectional tunnels, considering the possibility of motorists being exposed to smoke on both sides of a fire as described in the PIARC report [12] and many national tunnel ventilation guidelines. In contrast, in the NFPA 502 standard [1], there is no distinction between rural and urban tunnels with unidirectional traffic.
- Ventilation requirements could be compensated with other safety measures, e.g. shorter emergency distances. That can be evaluated by means of a risk analysis. That is also described in NFPA 502, but this approach has not yet seen widespread application in practice.

5.3. Flow Control

For fire ventilation, active control of longitudinal airflow is essential, in particular for urban highway tunnels, as described in the PIARC report [12] and the Compendium [23]. In principle, that would also be required to comply with actual NFPA 502 (2023 edition) requirements to 'control backlayering distance', or to 'keep longitudinal air velocity at low magnitudes where motorists can be on both sides of the fire side'. Until the 2020 edition, NFPA 502 required to achieve at least critical velocity in unidirectional traffic tunnels, ignoring the possibility of motorists downstream of the fire exposed to smoke. Active flow control has been applied in European tunnels for more than 20 years but not yet in the US [24].

However, in short tunnels, active flow control is not feasible, since there is no space for the necessary jet fans and anemometers at adequate distances, considering that jet fans close to a fire must not be operated, and instruments may provide distorted values, which need to be eliminated by a diligent plausibility check.

According to the PIARC report [12], without active flow control, a mechanical ventilation should not be operated at all when there is a possibility of congestions with motorists downstream of the fire exposed to smoke. That has been described e.g., by Bettelini for a 4-/5-lane highway lid [22]. Critical is particularly the case of a fire resulting from a rear-end crash at the end of a column of standing vehicles (see Figure 6).

Operating a tunnel ventilation without flow control may even increase the fire risk, as shall be explained for an example similar to the one in Figure 2. In short tunnels, the determining force is the wind pressure on the portals, which is in principle unknown and may strongly vary depending on the local meteorological conditions. Assuming a tunnel ventilation design case when the tunnel is filled with still standing vehicles in a congested situation over the whole length, the operating fans should achieve a flow velocity of approx. 3 m/s (critical velocity) against an assumed counter pressure of 10 Pa. But with a wind pressure of 10 Pa in the opposite direction and the tunnel filled only with 25% vehicles, the resulting flow velocity with the same number of operating fans would be 4.9 m/s. Such high flow velocities can fan a fire and accelerate downstream smoke spread, immediately disrupting smoke stratification. While small fires may allow for tenable conditions downstream due to smoke dilution within the large tunnel cross-section, large fires intensified by excessive airflow would endanger motorists exposed to the smoke.

A dynamic analysis shows that in case of congested traffic and strong wind against the traffic (see Figure 4), the smoke may have spread against traffic direction to the entry portal before that fire would be detected and any safety systems, particularly the mechanical ventilation, could react. When starting the jet fans in the smoke, a local backflow would occur, initially even driving the smoke against the traffic direction.

Moreover, the requirement to provide pressurization of the non-incident tube to prevent smoke spread through open cross passage doors (as specified e.g., in NFPA 502) cannot be met by providing only a row of fans at the entry portal.

5.4. Natural Smoke Exhaust

In some US highway lid project, designers proposed openings for natural smoke exhaust. In contrast, as part of refurbishment programs of some European tunnels, previous existing ceiling and wall openings had been closed based on operational experience. Arguments to be considered are:

- Natural smoke exhaust may work under favorable conditions of buoyancy driven flow, but in reality, the smoke is often driven by traffic or wind induced longitudinal flow past the opening along the tunnel.
- Ambient wind conditions outside the openings have a strong influence on smoke exhaust.
- Openings provide accident hotspots due to changing light conditions and entering rain and snow, increasing the risk.
- Openings are a source of noise, compromising one of the main benefits of the highway lid.

6. RISK ANALYSIS

6.1. General Description

Quantitative Risk Analysis (QRA) has been developed for a wide range of applications in the US, e.g., nuclear facilities, chemical industry and aerospace. There is a NPFA guide for evaluation of fire risks [2], and QRA is understood as an emerging practice for US road tunnels. In Europe, QRA is standardly applied to road tunnel projects, as described in PIARC [13] and many national guidelines and publications. For US road tunnel projects, we proposed to apply the German BASt methodology [20], [21] adapted to the conditions in the US.

The QRA focuses on accident risks based on statistical data, and on fire risk based on an event tree analysis for different scenarios. The scenarios are developed into an event tree, assigning probabilities to each scenario. The methodology has been described in the QRA report [20] and many publications (e.g. [26], [27]).

Analyzing only one or a few predetermined 'worst case' scenarios would lead to biased results. A serious analysis must evaluate 'worst cases' based on variations of traffic conditions (moving and standing vehicles), the type of fire, meteorological conditions, particularly wind on tunnel portals, fire buoyancy, and operating systems such as mechanical ventilation.

6.2. Traffic Scenarios

Beside wind pressure on the portals, moving traffic is the determining force influencing airflow and smoke spread in the initial phase of a fire in a tunnel, before the incident is detected and any systems can react. Therefore, defining different realistic traffic scenarios is essential for a serious analysis. Key scenarios are:

6.2.1. Free Flowing Unidirectional Traffic

During flowing unidirectional traffic, smoke spread is initially induced by moving traffic. Vehicles and motorists upstream are safe, vehicles downstream of fire should be able to drive out of the tunnel.

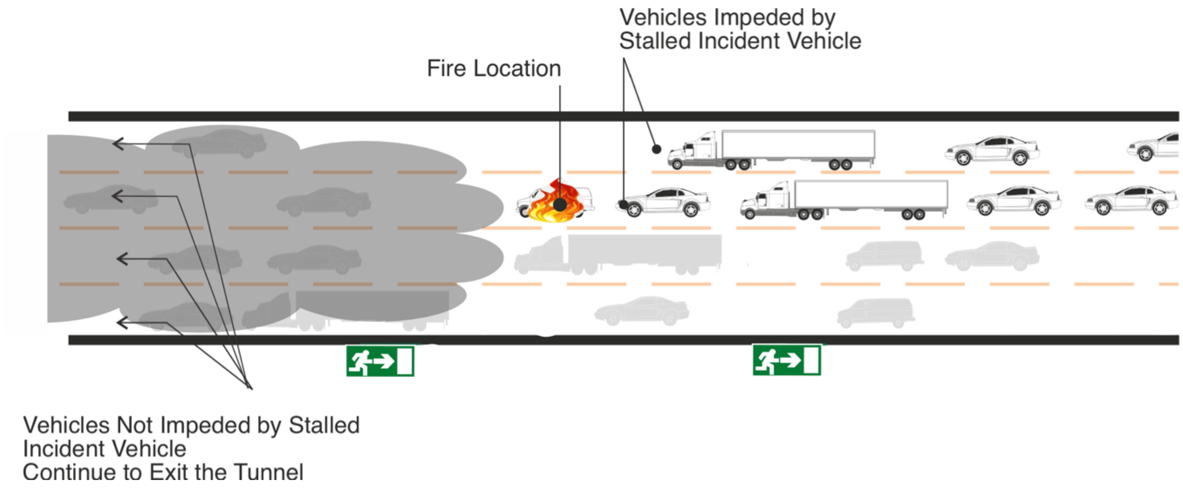

Figure 3: Free flowing unidirectional traffic

On the lanes behind the fire, vehicles are assumed to stop, as is modeled in common 1-D simulation tools (see Figure 7). However, in highway lids with 3 and more lanes, vehicles on the adjacent lanes are supposed to drive past the fire, further driving smoke spread in traffic direction. That must be considered for a realistic modeling.

As long as the traffic is moving, smoke is driven by the piston effect in the direction of the traffic. Motorists upstream (between the incident location and the entry portal) are situated in cold air and do not need to cross the active traffic lines to reach the cross passages.

Wind pressure and / or fire buoyancy may eventually lead to a flow reversal, which could be prevented by a mechanical ventilation.

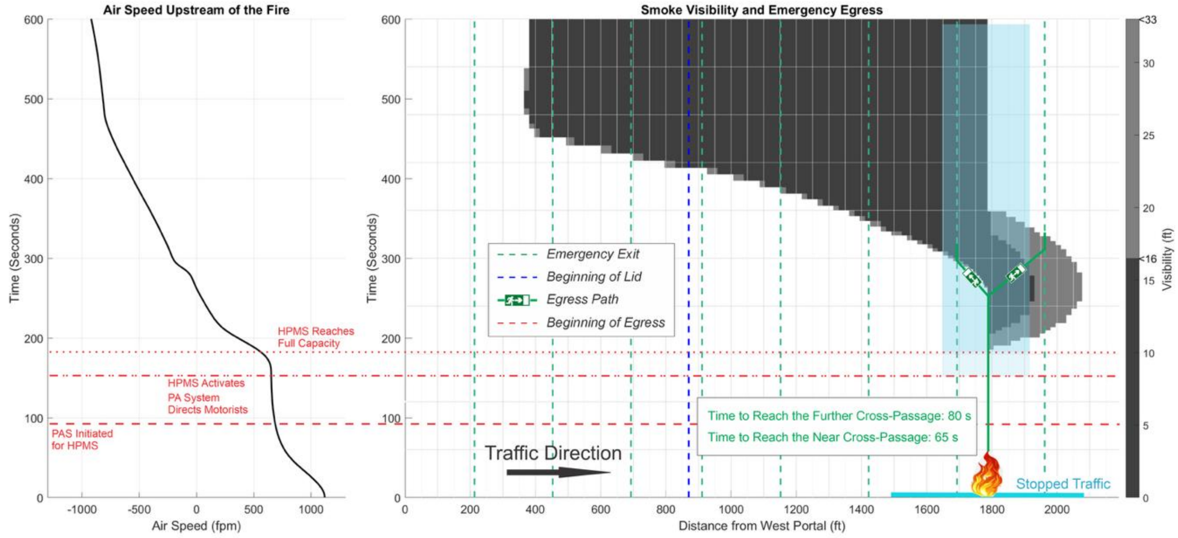

Figure 4: Simulation of flow and smoke spread with flow reversal

6.2.2. Congested Unidirectional Traffic

Congested traffic can be assumed as stop-and-go with low speed (e.g. 5 – 10 km/h). Still standing vehicles on all lanes for a long period are highly unlikely.

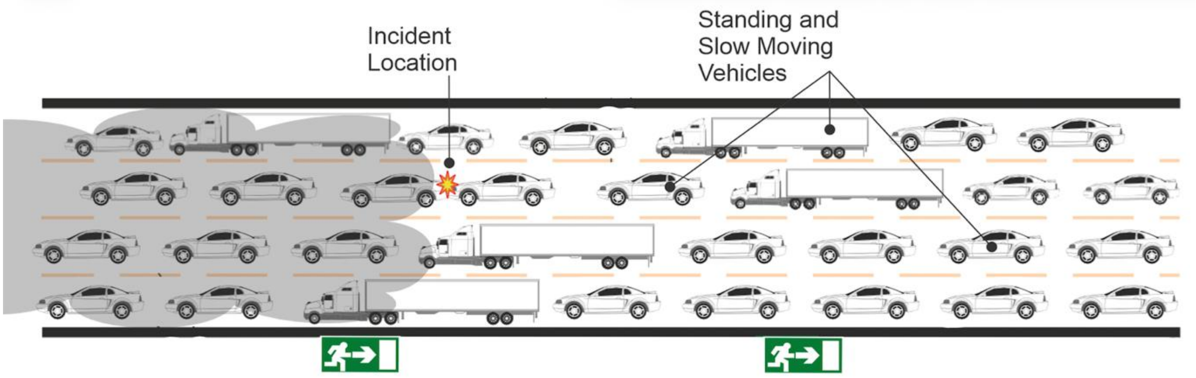

Figure 5: Congested unidirectional traffic

The likelihood of collisions with significant impact, and thus resulting fast developing large fires, is negligible. Nevertheless, fires from technical defects can occur and occasionally develop into large fires.

Strong wind pressure may lead to flow and smoke spread against traffic direction even in the initial phase. Cross passages serve for egress of motorists that are trapped in the smoke.

6.2.3. Unidirectional Traffic with Vehicles Blocked Downstream

The most dangerous scenario is when vehicles are blocked downstream of a fire, and motorists immediately exposed to smoke from a large fast developing fire. Such can occur e.g., resulting from a rear-end crash at a column of standing vehicles, which has led to some of the worst tunnel fire disasters (e.g., Tauern tunnel 1999, Yanhou tunnel 2014)

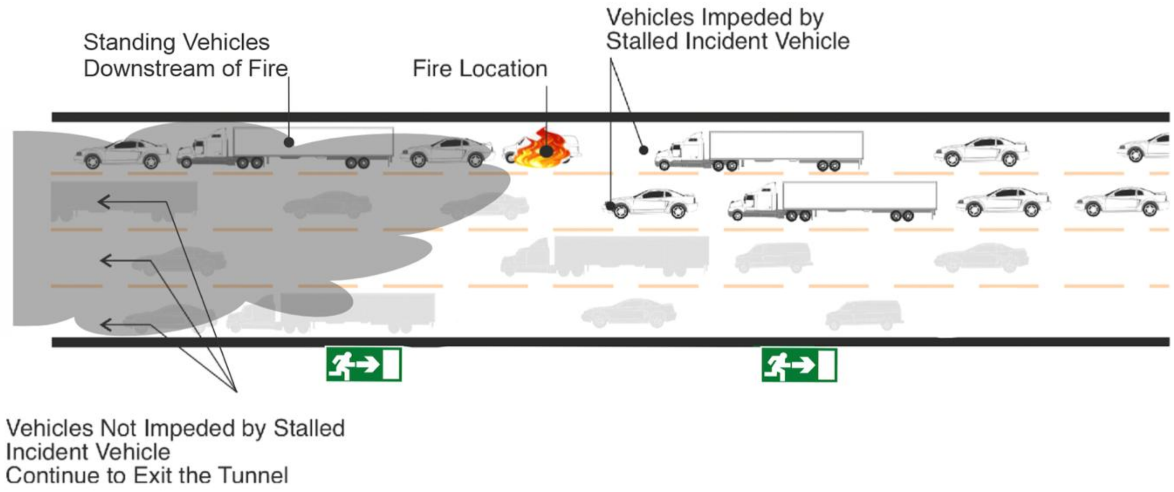

Figure 6: Unidirectional traffic with vehicles blocked downstream of the fire

Cross passages providing egress of motorists that are trapped downstream of the fire incident are essential. A mechanical longitudinal ventilation, blowing in traffic direction, would even deteriorate the conditions. A smoke exhaust system could limit the smoked up tunnel section, but the detection and reaction time needs to be considered when evaluating its benefit during the self rescue phase. Further, as explained in the Compendium [23], an additional risk arises due to the possibility of exhaust at the wrong place.

6.2.4. Bidirectional Traffic

Bidirectional traffic would also lead to motorists exposed to smoke on both sides of a fire, but is usually not considered in US urban highway lids. In case of a tunnel cell closure for maintenance or after an incident, the traffic is usually deviated to the surface road network.

6.3. 1-D vs 3-D modeling

Modeling is based on simplifications about aerodynamics and thermodynamics, using assumptions on physical parameters and boundary conditions.

Dynamic traffic and smoke spread modeling in road tunnels is usually conducted with 1-D models, as presented e.g. by Riess in 1999 [26], and developed into commercial simulation programs such as IDA.

However, actual models do not consider different traffic behavior on different lanes, as is the case in multiple lane highway tunnels. Therefore, we applied a combined approach with simulation of traffic on different lanes with different models which then needed to be combined.

1-D models do not display local effects, in particular smoke stratification and backlayering, asymmetric flow profiles, and turbulences, and therefore cannot be applied for complex geometrical structures. Smoke stratification during the evacuation phase provides tenable conditions up- and downstream of the fire, therefore a 1-D simulation considering only mean smoke densities is more conservative to assess how many motorists are affected by smoke in a given fire scenario, than a 3-D simulation with smoke stratification.

Most importantly, 1-D models can dynamically simulate moving and standing traffic and the resulting flow and smoke spread and are regularly validated by in-tunnel flow measurements and smoke detectors [25].

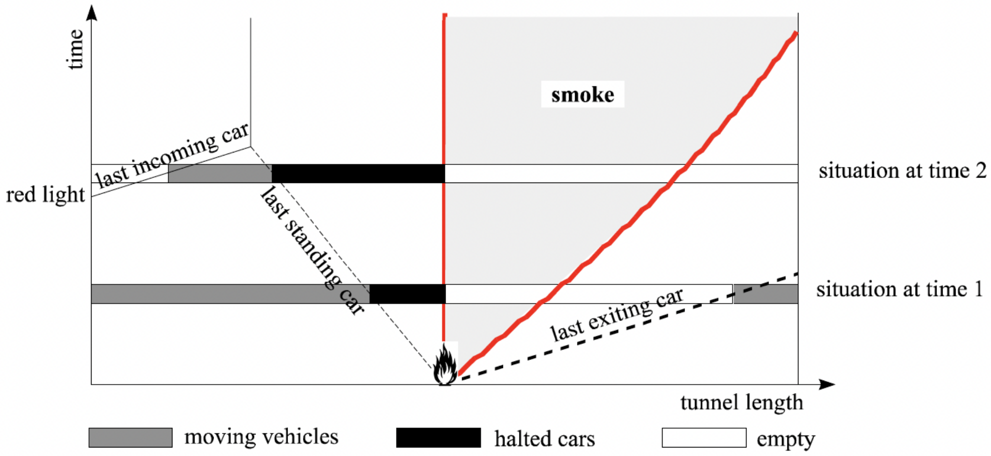

Figure 7: Traffic model and smoke spread for tunnel fire on 1-/2-lanes (from [26])

As a rule of thumb, a 1-D model is applicable for structures where the length is more than approx. 10x the width. For a 5 lane tunnel with a width of 25 m, that would mean that for lengths under approx. 250 m, 1-D modeling may be questionable.

On the other side, with 3-D models, moving vehicles cannot be adequately simulated with justifiable effort. 3-D models for road tunnels are useful for evaluating local aerodynamic effects, and fire modeling of buoyancy driven plumes, smoke stratification and backlayering. 3-D models can be particularly used to evaluate smoke stratification in critical scenarios that have been previously identified by 1-D simulations. Traffic induced flow can be modeled with a 1-D model and then applied to the 3-D model as boundary condition, however that is not possible in short tunnels where the 3-D model comprises of the whole tunnel length.

3-D models cannot appropriately model turbulences, therefore simplified turbulence models are applied. In real tunnels, particularly under traffic or with operating jet fans, the flow field is so highly turbulent that details of 3-D results may be questioned in principle.

3-D tunnel fire models have been validated by a series of full-scale tests (e.g., 1995 Memorial tunnel in the US), but a validation for project specific tunnel geometry and aerodynamic flow conditions, particularly under traffic, is not possible. 3-D simulations strongly depend on arbitrary boundary conditions and assumptions, therefore, do not provide additional precision in the results in comparison to 1-D analysis, when only the mean flow and smoke density is considered.

7. SUMMARY AND CONCLUSION

With a systematic safety concept approach, improved tunnel safety and cost savings are possible by focusing on measures with best effectiveness, in particular prevention, and reduction of safety measures with little or even negative benefit. An important aspect of a safety assessment is to consider unwanted side effects and evaluate ‘what can go wrong’, considering practical experience.

An example is tunnel ventilation. Mechanical ventilation in unidirectional traffic tunnels is typically used to prevent smoke from spreading against traffic flow, but inappropriate operation without flow control could also lead to increased smoke spread and destratification, making conditions worse for motorists downstream of the fire. For facilitating egress, emergency exits in short distances are more effective.

With a Quantitative Risk Analysis, the risks can be brought in the right perspective. The accident risk in road tunnels is a magnitude higher than the fire risk, and can be derived from excessive statistical data and tunnel specific adjustments. Simulations of smoke spread and egress are a useful tool to assess the fire risk. Smoke spread depends on many different factors, especially the moving traffic in the initial fire phase, meteorological boundary conditions, and fire buoyancy in tunnels with considerable slope. Therefore, a series of simulations have to be conducted for different fire scenarios under different boundary and initial conditions.

3-D simulations, such as those used for buoyancy-driven smoke spread in buildings, may have limited applicability to road tunnels, as they often cannot adequately simulate the critical factor of moving vehicles. On the other side, 1-D models are not applicable for very short and wide highway lids. There is a principal limit of useful modeling with justifiable effort for such projects.

Therefore, it is proposed applying an analytical approach that incorporates extensive experience from international tunnel safety practices and adapts it to the specific conditions of US highway lid projects.

In particular:

- Safety measures should be evaluated based on a diligent Safety Concept, focusing in first order on prevention.
- The utility and possible risks of mechanical ventilation should be carefully evaluated for short urban highway tunnels, particularly where active flow control is not feasible.

- Compensatory measures may comprise of preventive measures like traffic management and floor guidance lights, fast and reliable incident detection, emergency exits in short distances, and possibly active fire suppression (FFFS).

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