Suppression systems – Trade-offs & Benefits

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ABSTRACT

Suppression systems for road tunnels is a major topic of interest to the international tunnel community at present. While fixed water based fire suppression systems have been widely installed in tunnels in Australia and Japan, they have had limited use elsewhere.

There is, however, growing interest in the application of fire suppression including water mist, deluge systems and foam/water systems in tunnel environments. Research programs such as UPTUN and SOLIT have provided some basis for a better understanding of the role of suppression systems in road tunnel design.

This paper investigates about the possibilities of incorporating trade-offs in tunnel design when a suppression system is used, and it also discusses the different benefits that a suppression system could bring with it. Investigation of such matters must in part be dependant upon the design, operational and fire safety objectives for the tunnel and the extent to which asset protection and operational continuity are objectives as well as life safety of occupants.

To see if there is a potential for economic benefits when incorporating a suppression system a risk analysis approach has been used. This analysis takes into account the type of traffic foreseen, the traffic volume and the different types of consequences a vehicle fire could have upon the tunnel system.
INTRODUCTION

The provision of fixed fire suppression systems in road tunnels is now of major interest worldwide. Water based systems have been used widely in road tunnel design in Australia and Japan, and in a limited number of other places. They have traditionally used deluge systems.

The advent of the concept of water mist as well as foam/water systems for tunnels has created recent interest. This has been supported by research programs such as UPTUN [1] and SOLIT [2].

There has also been a change in attitude in internationally recognised standards such as PIARC [3] and NFPA 502 [4] for road tunnels. They are now, as a minimum, encouraging consideration of fire suppression systems as part of the fire protection measures for tunnel design.

Another factor is that major fires and other incidents have occurred in road tunnels that have drawn international attention to the risks. Traffic accidents, fires and other events have led to a loss of some 713 lives worldwide between 1995 and 2006 [5].

Design fires used for road tunnel design is typically based on a fire size of 30-50MW that determines the smoke control requirements, possible use of longitudinal jet fans or semi-transverse ducted systems. In the latter case, the exhaust quantity controls the size of the exhaust duct which in turn can affect the tunnel bore size. This has a major impact on tunnel construction costs.

The basis for 50MW (normally used in Australia) design fire would appear to have never been properly researched. While it is known from UPTUN and other research that heavy goods vehicle fires could reach 100-200MW, some would argue that 50MW takes into account the effectiveness of water based deluge systems utilized in Australia. On the other hand, others would argue a deluge system would never control a fire to 50MW, and if not suppressed at a lower fire size control is likely to be lost. They argue for a lower design fire of 20-30MW, based on the effectiveness of a deluge system.

This question of design fire systems for road tunnels with fire suppression systems warrants serious research. Potential benefits of a reduced fire size are: a reduction in smoke exhaust quantities which could lead to, more cost effective smoke control and reduced tunnel construction costs.

The authors are currently undertaking research aimed at better answering these questions, utilising the tools of quantitative risk assessment and cost-benefit analysis, particularly as it affects both life safety and financial performance for a typical toll road tunnel.

The authors are also conscious of the need for very clear agreement by all stakeholders of the range of fire scenarios on which any design fires are based, taking into account issues such as congested traffic, potential failure of key systems, errant vehicles and other low probability, high consequence events.

The aim is to provide guidance to tunnel owners, developers and operators as well as design teams and authorities on the potential benefits to aspects of design, including ventilation, from the installation of fixed fire suppression systems.
SUPPRESSION SYSTEMS

General
There are several possibilities when it comes to suppression of fires in tunnels. The suppression agent and its delivery, as well as system actuation, being automatic or manual, can all be different. Typically, fire suppression systems are divided into zones of 20-30m. The system is typically designed for up to three zones to operate simultaneously. The middle zone is where the fire is assumed to be located; the two adjacent zones are activated to ensure that the suppression system will cover the whole fire area.
We describe here only some typical systems:

Deluge systems
These are a normal specification requirement in Australia for road tunnels over 360m in length, as described in the RTA NSW [6] guidelines.

The system has open sprinklers, designed to deliver 10mm/min water density to the road surface. Again, in Australia, such systems are designed to be activated manually by an operator in a central control room. The operator will typically receive alarms from a video automatic incident detection (VAID) system, a linear heat detection system, other CCTV cameras and/or manual alarm calls. The aim is to discharge water quickly while the fire is still small, and less than 10-20MW.

The best example of this system operating in a major fire is the Burnley Tunnel Fire [7]. In this case, the deluge system and the ducted semi-transverse smoke controls system were activated rapidly, and together they controlled smoke volumes to a zone about 100m downstream of the fire, as designed.

Mist systems
A major concern in many of the countries is the amount of water required to be stored and used for annual testing and maintenance, and the need to treat large quantities of water after discharge before release back into the environment.

Water mist uses much lower water quantities but utilizes a much finer spray than with conventional sprinkler/deluge systems for more efficient suppression. As a result, pipes, tanks and pumps can be smaller, as well as water demand being lowered. Likewise, drainage volumes can potentially be lowered.

Some questions remain, in the view of these authors, regarding the performance of water mist. The impact of tunnel ventilation velocities on water mist appears to remain a major question. Carvel [8] in Stockholm presented some calculations which suggested higher ventilation velocities had a significant deleterious effect on water mist performance. More research appears to be needed to address these issues.

Nevertheless, it is understood that water mists systems have been installed in the Madrid M30 and Paris A86 tunnels in Europe.

Foam systems
Another potential tunnel suppression system is one based on a foam/water mix. Traditional concerns with use of for suppression water in tunnels has been based on its impact on flammable liquid fires. Foam water systems would appear to offer the benefits of suppression of fires, including flammable liquids, with a significant reduction in water quantities required.
DESIGN ISSUES

For ventilation in road tunnels, and for smoke control in the event of fire in particular, there are a number of design considerations, namely:

- What is the length of the tunnel, the traffic flows, vehicle mix and traffic management arrangements?
- What type of ventilation is being provided for normal traffic operations, including for congested and stopped traffic?
- What are the tunnel grades, location of portals, and merging tunnels for entry and exit?
- To what peak fire size must the smoke control system be designed?
- What egress arrangements are provided in the tunnel, including exits and cross passages, and what are the tenability acceptance criteria?
- Is a suppression system to be provided?
- Will there be a full-time skilled tunnel operators to manually activate suppression and ventilation systems?

The resultant smoke control, as a minimum (if a longitudinal system is appropriate), is typically a system of jet fans to provide a critical velocity of 3m/s that keeps the area, upstream of the fire, smoke free for fires up to the design fire size.

For such a system, the implication is that congested or stopped traffic will not occur downstream of the fire (in a uni-directional tunnel) or that smoke will be controlled or diluted sufficiently downstream of the fire to allow people evacuation.

More recently in Australia, smoke control in longer tunnels has been based on a ducted semi-transverse system. Air is drawn both downstream and upstream into the fire zone, with extract at the roof via a fire rated duct system and remote ventilation stations and exhaust stacks.

Design fire size

A key question is the design fire size upon which the design requirements (ventilation, passive fire protection, etc.) of the tunnel need to be based.

A typical project requirement is to base smoke control design on a peak heat release rate of 30-50MW [9] [10] for major urban tunnels carrying a mix of cars and trucks, up to heavy goods vehicles (HGV’s). Yet we know from work by Carvel [8] and others [11] that fires involving HGV’s and multiple vehicles can reach peak heat release rates of the order of 100-200MW.

The unstated assumption is that somehow the provision of a suppression system will limit the fire size to no more than 50MW. However, there appears to be no technical basis for this assumption, nor whether a suppression system that is activated when the fire has grown to 20, 30, or 40MW will control the fire or reduce it back to 10-20MW.

The design fire is the basis for all potential trade offs that can be applied to the design requirements. A suppression system will directly affect fire size but there are a number of factors that are of importance, the following three are considered to have a great impact on the fire size:

- Activation time
  This is clearly a very important issue. The activation time is strongly dependent on the evacuation and ventilation strategy. For some fire scenarios (including transverse or semi-transverse ventilation) a normal approach is to activate the suppression system once
evacuation is finished. In this way a smoke free layer is maintained during the evacuation period. The drawback is that the fire will grow during this period; the question is to what size? For a tunnel with a longitudinal ventilation system the suppression system should be activated as fast as possible.

- growth rate
The growth rate of the fire mainly depends on the ventilation velocity and the material burning. There is normally an initial phase with a slow increase of the HRR before the growth increases rapidly. The initial fire development is dependent on fire location, ignition source, etc. Figure 1 shows a few different HRR curves from a number of test series [12]. The increase in HRR for the fastest growing fires varied between 17-29 MW/min. It can be seen that in less than 5 minutes HRR of more than 50MW were reached (and in less then 10 minutes HRR of more than 100MW were reached). This clearly shows the importance of the activation time.

- effectiveness of suppression
There must surely be a limit for when a suppression system effectively can suppress and control a fire. This is probably dependent on the type of system used, but the system (whatever system used) will probably have to be activated before a fire size of 50MW is reached.

![Figure 1 HRR-Curves.](image)

It is clear that there are still questions and uncertainties related to the determination of a typical design fire size for a road vehicle tunnel (clearly an area for more research). However, the potential is that the installation of a suppression system should be able to justify the reduction of the design fire size to no more than 50MW, and potentially lower it to the order of 20MW, with smoke temperatures no greater than 100°C (212°F). This will bring considerable savings in ventilation design.
POTENTIAL TRADE OFFS

The provision of effective suppression systems in road tunnels has a number of potential benefits. These may include:

- **Life safety**
  It is arguable whether a deluge or water mist system offers life safety benefits in road tunnels, and there are varying opinions, based on recent conference discussions. Clearly it is dependent on the tunnel design and the operational procedures. However, in buildings, sprinklers reduce fire size, smoke quantities and smoke temperatures and there is good evidence for their effectiveness in terms of life safety. Therefore, this is likely to be the case in road tunnels also, although we do not yet have sufficient evidence.

- **Asset damage**
  We know that suppression systems have the potential to reduce damage to tunnel linings, road surfaces, and system and equipment installed within the tunnel. This was illustrated in the Burnley Tunnel Fire [7], with re-opening within 4 days and minimal damage from what was a large, rapidly growing fire that was quickly controlled. The absence of a suppression system in the I5 Santa Clarita Tunnel [13], Channel Tunnel (suppression systems for the train cargo area) [14], Mont Blanc Tunnel [5] and others and the extent of damage and time for the repair, reinstatement of systems, re-commissioning and rectification would clearly suggest that there are benefits of suppression in terms of reduction of asset damage.

- **Operational continuity**
  If a suppression system can reduce the fire to repair and re-commission, than the savings in revenue from toll tunnel operations can be considerable. In the Burnley Tunnel [7], the toll revenue lost was of the order of AUD $3million according to newspaper reports, and would probably have risen by the order of AUD $1million per day if operations had not been restored quickly.

- **Fire fighting**
  Fire brigades always prefer to fight a fire where a suppression system is operating. In Australia, they have been the strongest advocates of tunnel suppression. Since the design of the CityLink Tunnels [7] in the late 1990’s, they believe it allows them to approach the fire more quickly, to devote less resources (because life threatening conditions are lessened), and help reduce fire fighter exposure to these same life-threatening conditions, bringing distinct Occupation Health and Safety (OH&S) benefits.

- **Ventilation**
  For ventilation design there is a belief that there is a potential to reduce the smoke control air quantities too and base the design on a 20-30MW fire, rather than a 50MW or often 100-200MW fire.
  This becomes ever more important where a semi-transverse or full transverse system is required. In particular two issues: 1/ whether the duct work and its support needs to be fire rated and if so, can the rating be reduced where a suppression system is installed, 2/ the tunnel cross sectional area required to cater for the ductwork, less space for ducts would mean significant savings in construction costs.
  The benefit to ventilation is still being investigated by the authors to gauge the full financial benefits for ventilation design.

- **Tunnel lining**
  In Australia, and many other countries, the fire resistance level (FRL) of the tunnel lining is specified in performance terms based on 2hr FRL to the hydrocarbon curve in critical areas (those areas where collapse would be catastrophic) and 4hr FRL to ISO834 in other areas.
  This performance is achieved by various means, sometimes in combination, including:
- Sacrificial concrete
- Polypropylene fibres
- Passive lining over concrete

It may well be argued that, with a suppression system installed, there may be a reduction in FRL allowed, the required design to the hydrocarbon curve could be modified, or other trade-offs allowed.

Overall, it can be seen that there may be a number of potential benefits, both in terms of design and in terms of loss, including life safety, if suppression systems are installed in tunnels.

In particular, it may well be argued that if a tunnel design without deluge is adequate and meets national standards, then if a suppression system is provided, measures such as ventilation may be designed for a lower design fire size with subsequent financial trade-offs.
COST BENEFIT ANALYSIS

The benefits of fire suppression systems in road tunnels in terms of trade-offs still further investigation, and that research is on-going.

However, on the basis of asset protection and operational continuity for a typical toll road project, it appears that a risk assessment and financial analysis offers valuable insight into the benefits of a water-based deluge system. This is a first step before ventilation and smoke control systems are examined in more detail.

In buildings, sprinkler systems have been shown to offer real life safety benefits by controlling or extinguishing fires and reducing the likelihood of untenable conditions affecting building occupants. For road tunnels, the benefit of suppression systems in terms of life safety is more complex to evaluate, and have not been well studied. Only now are PIARC [3] and NFPA [4] even suggesting that suppression systems should be considered. And it may be argued that the principal benefits come from reducing damage to the tunnel lining and installed systems, as well as reducing operational interruption in the event of fire.

A first approach to cost-benefit analysis of suppression systems in road tunnels in this paper will concentrate on asset protection and operational continuity. It is based on a hypothetical but typical 6km urban road tunnel in Australia that has a zoned deluge system installed. In Australia, such a tunnel would most often be privately financed and operate as a toll road. The cost benefit analysis in this paper is of necessity a simplified version for the purposes of illustration in this paper. However it highlights the major issues.

Some key design and operational assumptions are as follows:

- Two tunnels, each uni-directional
- Tunnel length = 6km
- Tunnel road width = 12m
- Traffic flow = 100,000 vehicles/day in each tunnel
- Mix of vehicles
  - 93% cars
  - 7% trucks
- Vehicle tolls
  - AUD $5 for cars
  - AUD $15 for trucks
- Deluge system
  - Density of 10mm/min
  - Design area of 720m² (60m x 12m)
  - Design to AS 2118 - 2006
  - Tanks, pumps for 4 hours running
  - Manual activation by control room operator
  - Capital Cost of AUD $25 million (2009 Australian dollars)
  - Annual maintenance cost AUD $3 million (2009 Australian dollars)
Expected deluge system life = 30 years

Fire frequencies (based on PIARC 1999 [9])
- Car fires – 1.5 fires per 100 million veh.km
- Truck fires – 8 fires per 100 million veh.km
- Truck fires (some damage to tunnel) – 1 fire per 100 million veh.km
- Truck fires (very serious – damage to tunnel structure) – 0.2 fires per 100 million veh.km

For a road tunnel project of this size and traffic numbers assumed, the revenue would be calculated as follows:

- Total daily vehicle numbers = 100,000 x 2 = 200,000 veh/day
- Total cars/day = 93% x 200,000 = 186,000 cars/day
- Total trucks/day = 7% x 200,000 = 14,000 trucks/day
- Revenue/day = 14,000 x AUD $15.00 = AUD $210,000
- Revenue/day = 186,000 AUD $5.00 = AUD $930,000/day
- Total revenue/day = AUD $930,000 + AUD $210,000 = AUD $1,140,000

The next step in the cost benefit analysis is to establish the frequency of the key fire events and the estimated fire sizes. The frequency for this tunnel depends upon its length, the number of vehicles/day and frequency of fires.

Cars per year through tunnels
= 186,000 (veh/year) x 6 (km) x 365 (days/year)
= 4.07 x 10^8 cars/year

Trucks per year through tunnels
= 14,000 (veh/year) x 6 (km) x 365 (days/year)
= 0.306 x 10^8 trucks/year

For the four fire categories, the size of fire, the estimated asset damage (repair and replacement cost), and operational interruption times are estimated. These are based on the limited data available from fires such a Burnley Tunnel [7], Santa Clarita Tunnel [13], Mont Blanc [5], Channel Fire Tunnel [14] and other data in literature.

Estimates are made for this tunnel with and without a deluge system installed, see tables below.

<table>
<thead>
<tr>
<th>Fire Type</th>
<th>Without Deluge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fire Size (MW)</td>
</tr>
<tr>
<td>Car</td>
<td>5</td>
</tr>
<tr>
<td>Truck (small)</td>
<td>10</td>
</tr>
<tr>
<td>Truck (damage to tunnel)</td>
<td>30</td>
</tr>
<tr>
<td>Truck (damage to structure)</td>
<td>100-200</td>
</tr>
</tbody>
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Table 1 Asset damage estimates, without deluge.
Based upon the frequency of the different fire types, the analysed loss for each fire type can be calculated, based on the estimated loss in each event. This is illustrated in the tables below.

The differences in loss per year between AUD $65.1 million and AUD $10.0 million, and the values per year, seem high. However, in a pair urban tunnels of 6km in length and carrying 100,000 vehicles per day in each direction with 7% trucks, including HGV’s, the likelihood of fire is relatively high. The averages per year are of course, dominated by a relatively few fires and the fact that, even for short disruptions to operation, toll revenue loss of over $1 million per day can quickly accumulate.

The other part is that should a truck fire occur which affects overhead equipment, including lighting, signage, cabling, exhaust duct or has some impact on the structural lining, then the repair time and costs will be significant, and the time for incident investigation, government enquiries, re-testing and re-commissioning will all have significant associated time periods and costs.

If we assume the deluge system is 90% reliable, and 10% of the occasions when required to operate, the deluge system fails to control the fire, then we need to add 10% x AUD $65.1 million = AUD $6.5
million to the loss with the deluge system. This brings the loss per year with the deluge system to 
loss/year = AUD $10.0 million + AUD $6.5 million = AUD $16.5 million.

Thus the difference in loss per annum between installing a deluge system, and not installing a deluge 
system, are considerable based on this preliminary analysis if the total capital cost of the deluge system 
is AUD $25 million and the annual maintenance cost is AUD$3 million. The return on investment, 
even without a reduction in ventilation design and tunnel lining provisions, is substantial.

Further research is continuing into a more sophisticated financial analysis as key inputs and 
assumptions become more detailed. It is clear that a sensitivity analysis is also required to examine a 
number of key issues as follows:

(i) Traffic numbers – if traffic numbers were less, the revenue loss for operational 
disruption would be reduced, particularly for the non-deluge case.

(ii) Fire frequency – a reduction in fire frequency would affect both the deluge and non-
deluge cases, and reduce losses overall, and the difference between the deluge and non-deluge cases. However, even if the fire frequency was reduced by a factor of five, the cost-benefit of the deluge system in this scenario still appears very clear.

(iii) Operational interruption estimates – this is a critical factor on the revenue losses 
associated with interruption to operation, especially for the non-deluge case. Again, if 
the time for repair, reinstatement and re-commissioning after a very serious fire 
affecting the tunnel structure was reduced from 250 days to 100 days, the cost-benefit 
on this hypothetical tunnel design deluge system still appears financially attractive.

(iv) Repair/Reinstatement costs – the cost estimates and times for repair and reinstatement 
come from a brief review of fire incidents in tunnels such as Burnley Tunnel, Santa 
Clarita tunnel, and Mont Blanc. They seem reasonable estimates in the Australia 
context.

(v) Toll tariffs – the costs of $5/journey for cars and $15/journey for trucks again is 
representative of the current Australia toll tunnel environment. Any changes to tolls 
and revenue loss would change the cost-benefit. However, tolls are only likely to rise 
in the future.

In summary, there appears to be a prima facie case in terms of risk and cost-benefit to support the 
adoption of a deluge system in toll road tunnels in Australia. Further research and more sophisticated 
financial modelling is required to show the cost-benefit more accurately which can then in turn provide 
a basis for reduction in design fire size, and therefore savings in ventilation and structural provisions.

CONCLUSION

There is growing global interest in fire suppression system in road tunnels, including deluge system 
and water mist. There are a number of design and financial benefits that come from the installation of 
suppression systems.

A significant benefit is seen in the opportunity to reduce ventilation requirements as well as tunnel 
lining provisions, based on a reduced fire size or likelihood of a severe fire. 
A preliminary cost-benefit analysis has shown the advantage of deluge system installation, at least 
conceptually.

More research is needed, particularly into design fires and effects of suppression, in order to justify 
perceived benefits in terms of reduced design requirements such as ventilation/smoke control 
requirements and structural protection requirements in road tunnels.
REFERENCES


[9] PIARC, “Fire and smoke control in road tunnels”, PIARC Committee on Road Tunnels, (C5), 1999


