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Structural Fire Protection of Tunnels

The Limitations of "Trade-Off" When Using Fixed Fire Fighting Systems

Discussion Paper

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PREFACE

No internationally-recognised test standard exists to demonstrate the effectiveness of or the full-scale fire testing of Fixed Fire Fighting Systems (FFFS) in tunnels. Any testing undertaken is usually performed to answer a specific research question and therefore varies in set-up.

However, based on these research-based tests that examine specific situations, generic conclusions are being drawn that are encouraging the substitution of fire safety measures such as passive fire protection with FFFS. In reality, the actual effectiveness of FFFS in mitigating the effects of fires in tunnels is strongly dependent on the actual fire scenario along with the contributions of all other safety measures that could be present in the tunnel.

Since there are an infinite number of fire scenarios that may occur in practice, the findings of these research-based full-scale tests are not a suitable basis on which to draw generic conclusions about the effectiveness of FFFS in tunnels. For example:

- Because of the absence of standardised test methods, there is little consistency in the data between tests. For example, positions of thermocouples vary between tests and it is questionable if these measurements accurately reflect the maximum thermal exposure of the tunnel structure.
- There are many types of FFFS, producing wide variations in parameters such as nozzle positioning and spacing, water flow, droplet size, spray pattern and activation time.
- An FFFS is an installation which requires multiple components to function correctly, and which must be maintained to achieve this. A system that activates later than anticipated can have major consequences, because the structure may already have begun to fail before the system is activated and water is delivered to the fire.
- The active elements of an FFFS system comprises detection, alarm, activation and deployment components, each of which may be assemblies of other sub-systems, and which need software controls. Interaction between the software systems from the different manufacturers of the components used in the laboratory testing, may end up quite different to those installed in the actual tunnel. This can result in a variety of maintenance challenges, leading to undesired closure of tunnels, inaccurate deployment of water etc.
- Many fire scenarios are possible, which can be very different from a single laboratory-based test.
    - There are many different types, quantities, and combinations of combustible materials.
    - A fire may often be the consequence of a crash, meaning that scenarios can be widely different and hard to predict. Moreover, the fire development and propagation after the initial event will be influenced by the tunnel height, width and ventilation system, and combustible materials may or may not be shielded in this environment.
    - With the transition to alternative fuel vehicles (battery electric, hydrogen, gas, etc.) our understanding of fire scenarios is changing all the time. An FFFS that works well for one scenario may perform less well in any of the many other possible scenarios. An already installed FFFS will be difficult to adapt to new emerging risks.
    - Where the hazards involve potential explosions, then an FFFS could be damaged and therefore not operational at all.

An FFFS can contribute to the fire safety of a tunnel and, with thorough analysis and testing of these systems against a range of fire scenarios, they can offer additional, demonstrated, safety benefit. Although they cannot replace essential fire safety measures such as ventilation and passive fire protection, FFFS can be a valuable addition to fire mitigation measures, in a similar way to other high fire-risk sectors such as the petrochemical industry.

In many cases, cost-benefit (or similar) studies may reveal that a combination of other measures (e.g. traffic control, speed limits, dangerous goods monitoring, escape door distancing, ventilation, and passive fire protection) are effective. These methods can reduce fires from occurring and can provide a simple and effective and reliable means of protecting life and the asset; not only for new tunnels but also for existing ones.

The decision as to whether or not an FFFS is an option as a fire protection measure should be based not only on whether its works reliably to manage fires, but on an analysis of the TCO (total cost of ownership), including realistic maintenance and repair needs over the tunnel lifetime.

In this paper, the Authors review two articles concerning FFFS that were published in the Fire Protection Engineering magazine of SFPE. Ref. [1] and [2]. The SP report 2016:76 [3] referenced in [1] was also reviewed.

In particular, attention is paid to a conclusion drawn in [1] that if an FFFS is used to mitigate tunnel fires, a structural fire design based on the standard ISO 834 time-temperature curve is sufficient. The review includes an opinion about the scope of the tests on which this statement is based, the system design and validity of the conclusions for different fire scenarios in practice.

The review includes a literature study related to full scale fire testing of FFFS, supported by references to two reports, recently published by PIARC [4] and FHWA [5], about the use of FFFS in tunnels.

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1. Review of Articles

1.1. Li and Ingason Article from FPE Magazine and Underlying SP Report

The article by Li and Ingason [1] promotes the use of FFFS systems in tunnels based on some examples of past research (mostly done by RISE, previously known as SP).

The authors conclude that *“FFFS systems in tunnels are proven to limit fire size, cool the smoke and prevent fire spread to adjacent vehicles, thus aiding the protection of both tunnel users and the structure*” but do not clearly indicate the scope and limitations of this conclusion. The authors acknowledge the “*disadvantage of additional yield of toxic gasses such as carbon monoxide”* but state that “*this could be mitigated by early activation of the system to reduce the fire size”.*

The authors also acknowledge “*that installation of FFFS increases cost*” and therefore state “*that so-called technical trade off could be feasible”*. Such trade off “*could involve a reduction of the design fire for ventilation systems, tunnel structural protection systems and evacuation systems”*.

The possible trade-off in tunnel protection is supported by comparing measured maximum ceiling gas temperatures in fire tests with different types of FFFS [3] with nominal fire curves as the RWS curve, HC-curve and ISO 834 curve (Figure 1).

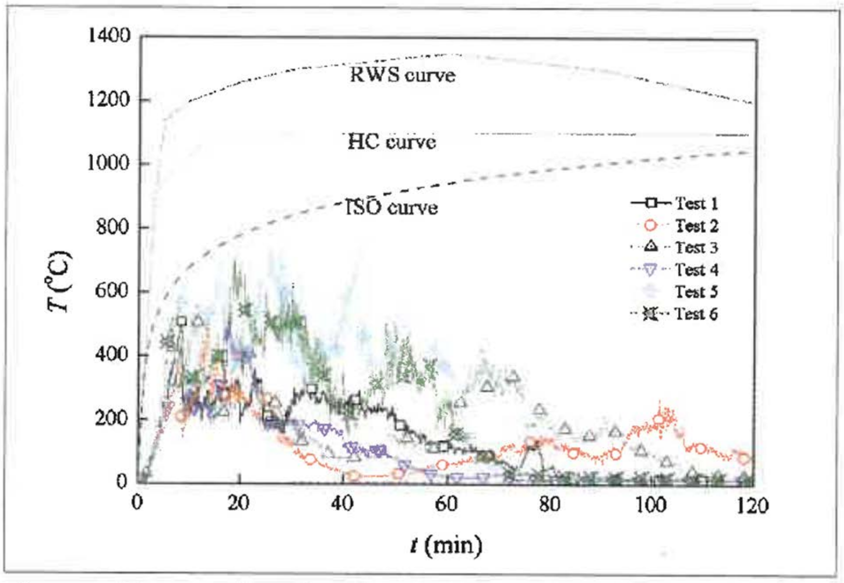

Figure 1 Measured maximum ceiling gas temperatures in 2016 Runehamar Tests 1-6 [2] shown in FPE article [1].

Based on these tests the authors state “*FFFS also performs very well in protecting the tunnel structure”* and more quantitatively they state that “*the ISO curve or even a lower time-temperature curve could be used for structural protection”*. It is unclear if this statement is referring to the FFFS that was being investigated, but the implication is that the finding is valid for all FFFS. Within this statement is the inherent assumption that a full, robust FFFS works with full reliability and provides early detection and adequate activation to manage the fire growth at an early stage.

Based on the actual information on the test provided in [3], we also observed that, due to the positions and limited number of temperature sensors in the test, substantial areas below the ceiling with temperatures over 800 °C can be missed during the test.

The position of the thermocouples is not clearly described and not included in the cross-section diagram in [3], but it is stated that *“The thermocouples (Type K, 0.5 mm) were located close (50 mm away) to the nozzle positions N2, N4, and N6”*. So, it is possible that the sensors were directly cooled by the water spray.

With these uncertainties over thermocouple positions from the reported test arrangements and the FFFS system being tested, it may not be the case that the test supports the conclusion that an ISO 834 fire test curve adequately describes the maximum thermal exposure of the ceiling.

When considering the statement on the ceiling temperatures reached in the test, and extrapolating that to real fires, ceiling temperatures in tunnels can be affected by a number of conditions that were not represented in the tests. For example:

- Location of ignition. The fuel (stack of wooden pallets) is ignited at floor level. Ignition on a higher level may lead to a faster temperature rise on the ceiling in the early stages of the fire (although this might be mitigated by earlier detection thus enabling earlier FFFS activation).

- Type of fuel load. Stack of wooden pallets were used as fuel load. However, this fuel load may not be representative to standard engine vehicles and their possible cargos (such as a flammable liquid), which can lead to different, much severe fire development, such as hydrocarbon fire. Moreover, alternative fuel vehicles (battery electric, hydrogen, gas, etc.) may pose a new threat due to not yet fully understood fire development and possible influence of a FFFS on it. For example, pressurised jet fires or even explosion can be caused when a hydrogen- or gas tank are involved in a fire. Also, water is not a suitable medium for extinguishing Li-ion battery fires.

- Ventilation speed. Higher ventilation speed may lead to faster fire growth, and thus promote higher temperatures in the early stage of the fire. However, to add complexity, this might be mitigated by more cool air being supplied.

- Position of fuel load with respect to tunnel wall. A position nearer to the wall opposite the nozzles may lead to less cooling by the water spray and thus higher temperatures, in particular if direct flame impingement to the wall occurs.

- Shielding of fire load. A fire load shielded with a steel roof may on one hand limit direct flame impingement and on the other hand reduce fire suppression.

- A moving vehicle on fire. Here the fire source moves relative to any target, which could also mean that the fire is outside the area of FFFS depending on configuration of the FFFS and tunnel.

Extrapolating the test results to other fuel types and tunnel configurations is incorrect. Higher ceiling temperatures for instance may occur due to:

- Lower tunnel ceiling. A lower ceiling means a shorter distance between the top of the fire load and the ceiling, yielding a higher probability of flame impingement and higher temperatures. In the reviewed tests this distance is (6.0 – 3.3) = 2.7 m. In reality smaller distances, e.g. (5.2 – 3.85) = 1.35 m may occur.
- A pool fire. In general, in order for a deluge sprinkler to mitigate the effects of a hydrocarbon liquid pool fire effectively, an additive such as Aqueous Film Forming Foam (AFFF) will be added to the water flow. If this is omitted (or not correctly implemented), then a pool fire, caused perhaps by a leaking tanker lead to higher ceiling temperatures. Large scale fire tests with a water mist system (WMS), however, have shown that, in a good design, an additive is not needed.

Considering the practicalities of an active system then higher ceiling temperatures can also occur due to full or partial failure of the FFFS performance. For example:

- Delayed and/or inaccurate activation. This may lead to temperatures rising rapidly before activation occurs, and eventually exceeding those of the ISO 834 fire test curve. This fault condition, and the resulting spalling of concrete, was demonstrated by Efectis in a large-scale fire test with a deluge sprinkler system that was purposely activated 8 minutes after detection instead of 4 minutes.[6]. Spalling of concrete is frequently seen in unprotected concrete elements after a few minutes of exposure during laboratory large scale fire tests. Activation can also occur too soon, leading to unwanted release of water in areas where it is not required. If water inventories are limited this introduces the risk of reduced water supply where it is needed, when it is needed.

- Delayed and/or decreased water supply. This might occur if water pipes break, nozzles melt or become damaged, or if nozzles are blocked by contaminants such as corrosion products or other solids. In the event of this occurring, the cooling capacity of a WMS reduces below the heat release of the fire, and a dangerous situation occurs with a sudden and rapid increase in gas temperatures.
- Delayed and/or inaccurate detection. Crashed vehicles may overturn and scatter their cargo across the road with the potential for inaccurate detection of the real fire location and consequently wrongly activated fire zones. And of course, detection might not accurately spot moving burning vehicles.

Finally, the general term "FFFS" (which are usually found as two variants in tunnels: deluge and mist) should be used with care. It suggests that the two are similar and interchangeable and that results of tests with deluge sprinklers (water sprays) are also valid for WMS and vice versa. Due to the different characteristics (e.g. droplet size, spray density, water pressure) of these systems, this is in general not the case as they function differently. A deluge sprinkler system achieves direct cooling of the tunnel structure by surface wetting whilst a WMS cools hot smoke and gasses. Both systems also mitigate the effects of fire on the tunnel structure by decreasing the fire burning rate, but they do this with different mechanisms (e.g. direct wetting of the fuel load in the case of deluge vs displacement of oxygen supply by a WMS). The result is that a 'realistic worse case' test for a deluge sprinkler may not be a 'realistic worse case' test for a WMS and vice versa.

The performance of an FFFS is based on a systems response, involving proper (timely and accurately related to the location(s)) detection, activation and deployment, which have been shown at best in limited combinations in a lab environment, under a limited number of varied parameters such as ventilation, fire growth rate, fuel types, fuel positions and distribution in the tunnel (length and cross section), etc., which deviate substantially from the actual tunnel situation.

1.2. Review of Cole Article in FPE Magazine [2]

The article by Andrew Cole [2] deals with "*the issues of design fires, time-temperature relationships, fire protection systems, ventilation systems and risk* "in the design process. According to the author the article is intended to "*give a high-level overview of methods that have been applied to address these"* … issues.

The author cites other well-known publications among which the latest PIARC publication [3]. Because of the "high-level approach" a technical review is less possible. Nevertheless, the following remarks can be made.

According to [2] "*using the RWS curve in tunnels with FFFS is onerous and a more appropriate design bases is the ISO Time-temperature curve"*. For the reasons covered in section 1.1 this is considered to be incorrect. Also the RWS curve is deemed representative for rapidly developing fires, such as pool fires caused by a leaking tanker containing a flammable liquid, which means that it is questionable if a deluge sprinkler without an additive will lower the time-temperature curve to the level of the ISO 834 time-temperature curve. And the use of an additive could be a problem due to environmental demands.

[2] also states "*for a true performance-based approach these curves could be further modified based on studies carried out with fire models"*. As an example, model studies are presented of a flammable liquids fire with "*a fire growth of 20 MW/min, capped on activation".* Unfortunately, no references are given. Efectis and other authors [4], [5] believe that the modelling of the effect of FFFS on the Heat Release Rate (HRR) of a fire is still very complicated and not so reliable as to be used without real fire tests to validate it.

2. Other Considerations

2.1. International

In January 2020 a report was published by the Federal Highway Administration (FHWA) of the USA about “Fixed Fire Fighting and Emergency Ventilation Systems for Highway Tunnels – Literature Survey and Synthesis” [4]. The study was performed by WSP – USA. The main goal of the study was to facilitate the design of the FFFS and emergency ventilation system (EVS) in an integrated manner. The effect of FFFS on structural passive fire protection requirements was also studied. The summary of the conclusions of that study are given in the frame below. (Note: FHRR = HRR)

> **Do FFFS reduce the structural passive fire protection requirements *(arising per NFPA 502)*; if so, by how much, and how does system reliability impact this?**
>
> It is demonstrated that FFFS can reduce the FHRR and hence the temperatures that the structure is exposed to. The degree of cooling will depend on the FFFS parameters as well as the fire source. CFD analysis can be used to characterize the thermal environment and to determine a suitable time-temperature curve for structural design. There is a strong coupling between the thermal environment analysis and the subsequent structural design, and coordination is critical. Passive fire protection requirements can be reduced, but key considerations include the thermal response of the concrete, the risk of structural failure (e.g. failures may be less tolerable if the tunnel is in unstable ground) and FFFS reliability. There is still a potential for spalling even with the use of FFFS; the delayed activation of FFFS allows concrete temperatures to increase, which is then coupled with thermal shock after the application of cooler water. A failure of the FFFS system will also increase the likelihood of spalling.
>
> The subject of FFFS reliability when considering compensations for passive fire protection is an area for further research and development. It is important to understand the consequences of FFFS failure for a structure relying on active fire protection, and the likelihood of FFFS failure. Ultimately, compensation of passive fire protection based on FFFS inclusion requires a consensus on an acceptable level of residual risk.

The conclusions in the FHWA report are based on several papers, among which those of SP (including [2]) and Efectis. The FFFS temperature-time curve derived by Efectis [6] is referenced in the FHWA report (Figure 6-5) as an example to show how to derive such a curve in a correct way.

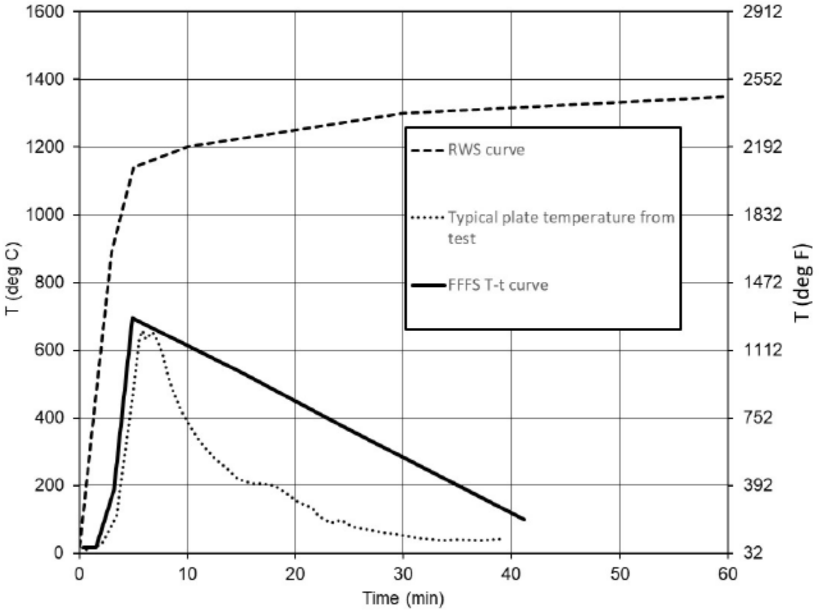

Figure 2 FFFS temperature-time curve (source figure 6-5 [5])

However, Efectis [6] puts some clear restrictions on the use of this reduced curve in practice, in particular:

- One should consider the probability and consequences of late activation or total system failure when using the ‘sprinklered fire curve’ to determine the thermal load on the tunnel structure. Based on the resulting risk this approach can then be accepted or rejected.
- In a probabilistic approach the probability of failure of the sprinkler system should be taken into account when assessing the fire resistance of the tunnel lining. This might lead to a decisive fire curve in between the traditional fire curves and the sprinklered fire curve presented in this paper.
- The FHWA report can give the impression that the FFFS-T curve is a design curve that takes into consideration the probability and consequences of partial or complete failure of the FFFS. However, given the restrictions provided by Efectis, and also to some extent in the FHWA report itself, it is clear that a full risk assessment should be done and the FFFS temperature-time curve cannot be used as a generic ‘sprinklered fire curve’.

The FHWA report also advocates the AST-method used by Efectis to derive the FFFS-T curve (note1). However, the AST-method cannot be used if a WMS is used instead of a deluge sprinkler, because the method does not include among others the effects of condensation of water mist droplets on the tunnel structure.

2.2. The Netherlands

RWS has undertaken a cost-benefit analysis of the use of WMS to reduce structural tunnel damage due to a large (> 50 MW) lorry fire. The case study was carried out for the tunnel A2 Leidsche Rijn [7]. The tunnel is protected against a 1-hour RWS fire curve with polypropylene fibres in the concrete. The total expected benefit of a WMS, i.e. reduction in fire damage costs (repair + society) was estimated at approx. 2.2 million Euro per year. The total expected costs to implement the WMS were however estimated much higher, namely at 5.4 million Euro per year, of which 5.0 million Euro society costs are to cover regular WMS maintenance (which involves periodic closing of the tunnel).

Based on these results RWS has decided not to apply FFFS (WMS) in their tunnels.

3. CONCLUSIONS

3.1. Maturity of FFFS testing methods

No Internationally-recognised test standard exists for the full-scale fire testing of Fixed Fire Fighting Systems in tunnels. Tests are mostly performed to answer a specific research question and vary strongly in set-up. The results of fire tests are therefore valid for the tested situation, i.e. the actual fire scenario in combination with the complete set of safety measures in the tunnel. This means that a FFFS with different parameters (centre-to-centre distance of nozzles, direction of nozzles, spray pattern, water pressure), different type of fuel load and changes to the shielding/covering of the fuel load may significantly influence the fire development and therefore the efficiency of the FFFS.

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[1] The method is based on a combination of the Adiabatic Surface Temperature (AST) method and measured temperatures on and in concrete tile specimens positioned against the tunnel ceiling. With this method a high resolution measurement grid was achieved.

Full scale tests are seldom, if at all, undertaken with all components included and for different more realistic fire scenarios (e.g. multiple fires, or moving/travelling fires, which can be very challenging for the detection and activation and operation of FFFSs).

Only a large-scale fire test is able to reliably prove that a FFFS could work properly, with all components included. Such a test needs to measure the temperature conditions, to which the concrete is exposed in a way that is representative for the full exposed area, i.e. with many evenly spread thermocouples. However, if one or more parameters of the test setup changes (activation, ventilation conditions, size or type of fuel load, dimensions of the tunnel, parameters of the FFFS), the results of the change(s) shall be confirmed by performing more tests, and/or build in redundancy and robustness in the actual application (more costly).

Assessing the fire performance of FFFS in tunnels is still in the stage of empirical laboratory testing, and if the test setup is not correctly designed and the FFFS is not extensively tested, it does not address the entire system (including detection, activation, deployment) under a sufficiently large number of varying parameters (including geometrical differences compared to the real tunnel, climate conditions and ventilation, realistic fire loads and their positions in the tunnel, etc.)

Since an infinite number of fire scenarios may occur in practice, the existing full-scale test results discussed in this paper are not suitable to draw generic conclusions about the effectiveness of FFFS in tunnels.

This is very different to the use of passive fire protection to protect the structure, which works regardless of the fire scenario (location, development, …). This means that passive fire protection may be assessed with a limited number of standard fire tests using a single time-temperature curve deemed representative for the credible worst case.

3.2. Fire curve in tunnels equipped with FFFS

Based on such tests, some authors suggest that in case of a sprinkler the typical free-burning fire curves such as the RWS-curve can be replaced by generic building fire curves such as the standard (ISO 834) fire curve. However, there are several reasons why individual fire test results with FFFS cannot be claimed as generic solutions: By absence of standardised test methods, there is little consistency in the data. Positions of thermocouples vary and it is questionable if these measurements accurately reflect the maximum thermal exposure of the tunnel structure.

- There are many types of FFFS which vary in, for example, nozzle positioning and spacing, water flow, droplet size, spray pattern and activation time.
- An FFFS is an installation which requires multiple components to function correctly. This depends strongly on correct maintenance. A system that activates later than anticipated may have great negative consequences, because in the first few minutes of the fire the concrete structure may already begin to spall.
- Many fire scenarios may occur, with different types, quantities, combinations, geometries and possible shielding of combustible materials. Also, combustible materials change due to the transition to alternative fuel vehicles (battery electric, hydrogen, gas, etc.). A fire may often be the consequence of a crash, meaning that scenarios can be widely different and hard to predict. Moreover, the fire development and propagation will be influenced by the tunnel height, width and ventilation system. An FFFS system that works well for one scenario may perform less in any of the many other possible scenarios. Also, an already installed system will be very difficult to adapt to new risks. In case of explosion, the FFFS could be damaged and therefore not operational at all.

3.3. The trade-off approach to structural fire protection in tunnels is flawed

Trade-off is an approach based on cost reductions rather than on safety arguments. One system is presented as removing the need for other systems, thereby saving money. However, the fundamental approach must always be that the actual safety required is the leading consideration, and then various safety measures can be weighed individually and in combination to reach the optimum safety level at a reasonable cost. This is the concept of reducing risks to As Low As Reasonably Practicable (ALARP).

One important risk of a trade-off approach using FFFS is that all safety is provided by one system, and that system is an active system. This is an approach which imposes extremely high reliability and availability requirements on that one system, which must be demonstrated as always being high. Therefore, a trade-off approach that relies on FFFS will increase the maintenance burden to ensure that those demands are always satisfied and can quickly exceed the original cost savings.

When the trade-off promotes an active system over a passive system to provide the same safety benefit then that is a challenge to inherently safer design concepts. At a basic level there is less to go wrong with a passive system than an active system that provides the same level of structural fire protection.

To support a trade-off decision, an objective basis of comparison is needed. This is not available when considering active and passive fire protection measures because systems don’t just act alone but also in combination, and the proven performance of passive fire protection and very mature testing methods are difficult to compare with the testing methods for FFFS which require extensive full scale testing for a very limited scope of validity. At present, the justification for trade-off in terms of lowering temperatures by using FFFS overlooks the limitations of the existing research to date, and its limited applicability to real scenarios. Any comparison is invalid.

And a fair cost comparison should address the entire Life Cycle Analysis and associated costs, including inspection and maintenance, upgrade, environmental effects related to effluent of contaminated water, etc.

Good safer design principles endorse the use of diverse means of risk reduction. The impact of all fire safety measures, including FFFSs, should be considered as part of a holistic fire and safety risk assessment. This approach is also not common practice in other buildings codes but, if done at all, it is not the fire temperatures that are reduced by the introduction of active FFFS measures but the required fire resistance times.

Instead of trade-off, the joint contribution of fire safety measures should be considered. FFFS can contribute to the fire safety of a tunnel structure but to understand how requires a thorough analysis and testing of these systems against a range of fire scenarios. FFFS cannot replace essential fire safety measures such as ventilation and passive fire protection but can be a valuable addition to increase the fire safety, in a similar way as in other high fire-risk sectors such as the petrochemical industry.

The Alpine tunnel fires in the late 1900’s and early 2000’s have shown that there is a need for a more holistic approach using a variety of complementary fire safety measures, rather than relaxing the requirements, or putting total reliability on one fire safety system. New trends in transportation and energy sources (e.g. road-trains, electrical vehicles, traffic growth, …) give rise to new fire threats that are likely to increase the need for a holistic approach. It is the authors opinion that cost-driven trade-off and value engineering are counter-productive towards tackling these trends and where implemented require a thorough understanding of the hazards and risks associated with a given course of action.

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