

Challenges for Use of Fixed Fire Suppression Systems in Road Tunnel Fire Protection

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1. Introduction

Road tunnels are critical components of most transportation systems around the world. Ensuring fire safety in road tunnels is more challenging than ever due to the specific features of the tunnels, increased traffic and inadequate safety rules. The analysis of actual fire incidents has indicated that fires in tunnels tend to be hotter, last longer, and to be more destructive than was generally expected. This made rescue operations and fire extinguishment by the fire services more difficult [1-3].

Fixed fire suppression systems are used as an effective fire protection measure in many areas of the built environment. However, many countries have not considered them necessary or even acceptable for tunnel protection. There are concerns on the use of these systems in tunnel environments, such as the visibility reduction during evacuation caused by water discharge, the associated high cost for installation and maintenance, their performance in suppressing shielded fires, potential hazards presented by hot steam and deflagration generated in suppressing large flammable fuel fires, as well as limited knowledge on the most suitable suppression systems for tunnel protection [4-7].

However, with a significant increase in the number and the scale of fire accidents in tunnels around the world over the last ten years there is renewed interest in the use of fixed fire suppression systems for tunnel protection. Fixed fire suppression systems are suggested for installation in urban tunnels where heavy goods vehicles are mixed with private passenger cars, which would protect the tunnel structure and limit the spread of

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the fire [8]. For example, Japanese authorities have developed guidelines for the use of fixed fire suppression systems for tunnel protection [9]. Approximately 80 road tunnels in Japan are equipped with water spray fire suppression systems. Also, water-based deluge systems are recommended for use in all new Australian road tunnels [10].

The authorities in some countries are also considering using fire suppression systems to reduce fire risks in road tunnels, when they plan to permit the transportation of all kinds of goods in road traffic tunnels to cope with increasing economic activities [11]. It is expected that fire suppression systems can be used to control fire and its spread in the tunnel in order to minimize tunnel structure damage and business interruption caused by fire incidents [9-11].

Research activities have been initiated over the last ten years, not only to study the use of traditional sprinkler systems for tunnel protection, but also to explore the general suitability of water mist, compressed air foam and other fire suppression technologies for this application. Studies have demonstrated the feasibility of using several fire suppression technologies for tunnel protection, but at the same time, some concerns on the use of such systems still exist. This paper reviews current research activities into the use of water-based fire suppression systems for tunnel protection, and identifies some of the challenges associated with the use of these systems in tunnel applications.

2. Sprinkler/Spray Systems

One of the early test programs to study the performance of sprinklers for tunnel protection was conducted in the Ofenegg tunnel in Switzerland in 1965 [12]. The tunnel was an old single track railway tunnel, 4 m wide at the base and 6 m high. Three fire sizes using aircraft petrol fuel were used in the test program: (a) 100L and 6.6 m² pool size; (b) 500 L and 47.5 m² pool size; and (c) 1000 L and 95 m² pool size. Two lines of sprinklers were installed on the ceiling of the tunnel. The water capacity was 19 L/min.m². No information on the activation time of the sprinkler system was reported.

The fires developed very quickly during the tests and the maximum temperature was reached 1 to 2 minutes after ignition. Temperatures in the tunnel were quite high with maximum temperatures near the ceiling ranging from 1200°C to 1400°C prior to sprinkler activation.

The sprinklers were able to extinguish all of the fires within a short time. However, a large amount of hot steam was generated during fire suppression. Visibility was significantly reduced due to the hot steam and cooling of the smoke layer by the sprinklers' discharge. Smoke and hot steam were pushed a considerable distance from the fire site, resulting in higher temperatures than without sprinklers at some locations in the tunnel.

After the fire was extinguished, the fuel continued to evaporate and the vapour spread along the tunnel. The vapour was re-ignited in the vicinity of the fire zone after it reached the critical concentration. The deflagration created by re-ignition caused extensive damage to the test setup and the ventilation installation in the tunnel.

In 2001, to further examine steam-formation and the effectiveness of sprinklers during fire suppression in tunnel incidents, the authorities in the Netherlands conducted a series of fire tests with sprinklers in the Benelux tunnel [11]. The test tunnel was an operating road tunnel, 9.8 m wide and 5.1 m high. Various fire scenarios were used to simulate stationary vehicle fires, including a van loaded with wood cribs, a high goods vehicle (HGV) fire loaded with wood pallets and an aluminum truck cabin loaded with wood cribs. No liquid fuel fire was used in the tests. The fire size in the test program ranged from 15 MW to 40 MW.

Two sprinkler zones were installed in the test tunnel. The length of Zone I was 17.5 m and Zone II was 20 m long. The discharged water quantity was 12.5 L/min.m², which was ~1/3rd lower than those used in the Ofenegg test program. Activation time of the sprinklers in the tests ranged from 6 min to 22 min after ignition of the fire source.

In order to focus on the study of the air cooling and steam-formation generated by sprinklers, the mechanical longitudinal ventilation in the tunnel was not activated during tests. The air speed in the tunnel was approximately 0-1 m/s in three tests, and approximately 3 m/s in one test.

For all tests, the air temperature upstream and downstream of the fire decreased from approximately 250-350°C to 20-30°C in a very short period of time after sprinkler activation, which prevented the fire spread from one vehicle to others. The smoke layer was disturbed with the activation of the sprinklers, and visibility was almost entirely obstructed. It took 5-15 min to improve visibility. No significant steam-formation and no deflagration were observed in the test program.

Japanese authorities have conducted a series of fire tests to study the use of water spray for tunnel protection and some of these studies have recently been reported. For example, a series of tests were conducted in an operating road tunnel with a large cross-section area (115m²) [9] using a 5 MW gasoline pool fire where the performance of three different types of spray systems was investigated. The water density used in the tests was 6 L/min.m², which was much lower than that used in the European tunnels (i.e. half of that used in the Benelux tunnel tests). Other Japanese test programs involved fire sizes from 4 m² and 9 m² gasoline pool fires to a bus fire in an operating road tunnel [13, 14]. The results of these tests showed that the air temperature in the tunnel was quickly decreased to the ambient air temperature with the activation of the spray system. There was no report on smoke distribution and steam generation during fire suppression.

Japanese authorities also studied the activation time of a water spray system in a fire incident to maximize the advantages of the water spray system and to minimize errors or confusion by tunnel operators [9]. They chose that the activation time of the water spray system was 3 minutes for a uni-directional tunnel, and 10 minutes for a bi-directional tunnel after fire was detected. There was no requirement for human intervention except for special cases. These activating timings were determined based on the risk assessment analysis in tunnels and experimental data. Based on these studies,

automatic operation of water spray discharge was adopted in Japanese tunnels. Fire incidents, after adopting the new automatic operation procedure, showed that water spray did not affect evacuation, and the water spray system was effective in minimizing the fire size and protected the tunnel and facilities.

The main objectives for the use of water spray systems in Japanese tunnels were to [9]:

- Suppress and cool down the fire;
- Prevent fire spread in the direct vicinity of the fire;
- Protect tunnel structure and its facilities; and
- Support firefighting activities.

The Japanese authorities developed requirements and guidelines for installing water spray systems in tunnels [9]. Water spray systems should be installed in tunnels with a length of 3000 m or longer and with traffic volumes of 4000 vehicles/day or more. The standard water volume is 6 L/min.m² with at least a discharge pressure of 0.34 MPa. One spray section is 50 m in longitudinal length and the water supply must be longer than 40 minutes.

3. Foam Water Suppression Systems

One recommendation for the use of fixed fire suppression systems for tunnel protection is to use foam additives to protect against possible flammable liquid fuel or chemical fires [4, 5]. The feasibility of the use of foam–water sprinkler systems against pool fires was investigated in large-scale fire tests conducted in the Memorial tunnel [7]. Diesel pool fires with heat release rates of 10, 20, 50 and 100 MW were used in the test program. The water density with foam additives (3% AFFF) ranged from 2.4 L/min.m² to 3.8 L/min.m². It was reported that the fires were extinguished in less than 30 s in all four tests. The effectiveness of the deluge foam-water sprinkler system was not affected

by a longitudinal ventilation velocity of 4.2 m/s. No details on the changes in air temperature, smoke distribution and steam generation during suppression were reported.

Recently, the European TNO project conducted a series of full-scale fire tests to evaluate the effectiveness of a fixed compressed air foam (CAF) system for tunnel protection [15]. The tests were conducted in the Runahamar tunnel in Norway in 2005. The tunnel was 6 m high, 9 m wide and 1600 m long. Two types of large simulated tunnel fires were used. The first one was a fully developed solid fuel fire (wood pallets) with a volume of 100 m³ and a heat release rate of up to 300 MW. The second fire was a fully developed fire of diesel pool with an area of 100 m² and a heat release rate of 200 MW. The water density of the CAF system used in the tests was up to 5.6 L/m².min. The CAF system was activated at 2-3 minutes for diesel fuel fires and 5-10 minutes for solid fuel fires after ignition. The jet fan systems in the tunnel were running to maintain the longitudinal air velocity at 2~3 m/s during the tests and to investigate the effect of ventilation conditions on the effectiveness of the CAF system.

During the tests, the CAF system was successful in rapidly extinguishing the large diesel fuel fire. It also controlled the solid fuel fires, but could not extinguish them. The air temperature upstream of the fire was cooled down to 50°C, allowing firefighters equipped with appropriate protective equipment to approach the fire. The air temperature downstream of the fire was also cooled down to below 100°C, preventing fire spread in the tunnel. The visibility in the tunnel was completely lost before the discharge of the CAF system, because of large fire size and long pre-burn period. No significant steam and no deflagration were generated during fire suppression in the tests.

4. Water Mist Fire Suppression Systems

Compared to sprinklers and spray suppression systems, water droplets generated by the water mist systems are smaller and they have advantages in fire suppression through using less water and quickly cooling the air temperature. A number of research

projects have been undertaken in Europe over the last few years to explore the suitability of water mist systems for tunnel protection.

For the EU UPTUN Project [16], tests were conducted in a tunnel 5 m high, 8 m wide and 100 m long. The air velocity in the tunnel was maintained at 1~2.5 m/s during the tests and the fires used in the tests included open diesel fuel pool fires, sheltered diesel pool fires and partly sheltered and fully developed wood pallet fires. Fire sizes varied from 2 to 25 MW. The performance of both low and high-pressure systems was evaluated where the discharge rate of water varied from 1 to 3.5 L/min.m² for low-pressure systems and 0.6 to 2.3 L/min.m² for high-pressure systems. These were lower flow rates than the foam sprinkler system tested in the Memorial tunnel. The activating time of the water mist systems was 2~3 minutes after ignition for the liquid fuel fires. The solid fuel fires were fully developed prior to activation.

Test results showed that the effectiveness of the water mist system in controlling a fire was strongly dependent on the fire size, nozzle type and location and water discharge rate used in the test program. For diesel pool fires, the reduction in the heat release rate through the use of water mist was 0~60% for the fires with a size of 5 MW, 0~80% for the fires with sizes of 5~13 MW, and 10~80% for the fires with a size of 20 MW. For solid fuel fires, the reduction in the heat release rate was 40~80% for the fires with a size up to 20 MW. The visibility conditions downstream of the fire were not improved during the first few minutes after activation of the suppression system. However, visibility generally improved as the fire size and the heat release rate were reduced. There was no report on steam generated during suppression.

A series of water mist tests were also recently conducted in the A86 East tunnel in Switzerland [17], which has dimensions of 9.3 m wide and 2.55 m high. The water mist system, using water flow rates varying from 0.5 to 1.5 L/min.m², was designed to keep the heat release rate from a vehicle fire to a reasonable level, and not to extinguish the fire. Activation of the water mist system occurred 8 minutes after ignition. The fires

used in the tests were vehicle fires, simulating a crash incident involving four vehicles. Peak heat release rates of these fires were reported to be approximately 20MW.

Test results showed that with the discharge of the water mist system, the fire size was controlled, and the fire did not spread toward adjacent vehicles. The water mist cooled the combustion gases and reduced the radiative heat flux. Temperature measurements in a vehicle located 75 m downstream of the fire showed that water mist reduced the external air temperature to 40°C and the temperature inside the vehicle was kept at 25°C. The maximum CO and CO₂ concentrations measured in tests were approximately 775 ppm and 2.0% outside the vehicle, and 210 ppm and 0.64% inside the vehicle. The discharge of water mist improved the tenability and survival conditions inside the vehicle. The visibility upstream of the fire was reduced after the discharge of the water mist system but the visibility conditions downstream of the fire was improved.

5. Summary

Recent research has shown that fixed water-based fire suppression systems can control fires, cool the air temperature, and prevent the fire spreading in a tunnel. However, their capabilities to extinguish tunnel fires depend on the type, size and location of the fire, as well as the type of fire suppression system used. A CAF system did extinguish an open diesel pool fires but could only control solid fuel fires.

Visibility in the tunnels was reduced with the discharge of water-based systems, which would negatively affect evacuation. No significant steam generation and no deflagration resulting in re-ignition were reported in the tests using foam sprinklers, spray systems, CAF systems or water mist systems. In these tests, the fuel sources were small gasoline pool fires, large diesel pool fires or solid fuel fires, and the amount of water used was limited. However, these phenomena were observed in tests using sprinklers with high water flow rates to extinguish large petrol fires in a small railway tunnel.

Current foam sprinkler systems, water spray systems in the Japanese tunnel, CAF systems and water mist systems are not designed to extinguish the fire but for controlling the fire size, protecting the tunnel structure and facilities, and supporting firefighting activities. The amount of water discharged from these systems is much lower than those from conventional sprinklers.

Research on water-based fire suppression systems for tunnel protection is very limited. Studies on the feasibility of using CAF systems and water mist systems for tunnel protection were only recently initiated. The fire type, size and location used for evaluating the effectiveness of fire suppression systems changed from one test program to another. Also, the fire tests were mainly focused on fully developed solid fuel fires with long pre-burn periods. More research is needed to develop appropriate design fire scenarios for evaluating various fire suppression technologies for tunnel protection; to study the improvement of these systems in combination with fire detection systems; to study the impact of water quantity on the generation of steam and deflagrations when suppressing large flammable liquid pool fires; and to study water-based fire suppression systems against various tunnel fire incidents.

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