CFD Simulation of Water Mist and Sprinkler System In Resalat Tunnel of Tehran

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Abstract

Due to the increasing rate of vehicle traffic and limited real estate, the construction and complexity of road tunnels are substantially increasing throughout the world and safety of them has become an important concern among officials, researchers and engineers. As a result of multiple-death fires that have occurred in past years in highway tunnels in Europe, for example the Mont Blanc and St. Gotthard tunnel fires; there is a growing demand on public highway officials to meet a minimum standard for life safety in tunnels. Regarding that Tehran is one of the most crowded cities of the world and since the history of constructing the first road tunnel of this city dates back to 2006, up to now no practical fire test has been conducted in these tunnels. Computer simulation is one of most economical and flexible methods to get the knowledge about fire processes under different conditions. So in this study the capability of FDS (Fire Dynamic Simulator) has been used to simulate a vehicle fire in Resalat tunnel to analyze the consequences. Also sprinkler and water mist systems have been modeled in the same fire conditions in Resalat tunnel to find their effectiveness in a confined area. Comparing the results it has been extracted that using automatic sprinkler and water mist systems in Resalat tunnel have both advantages and disadvantages. But it is better to use such systems to control the fire origin until firemen arrive and extinguish fire.

Keywords :Resalat tunnel; tunnel fire; sprinkler system; water mist system; CFD; FDS; NFPA502

1. Introduction

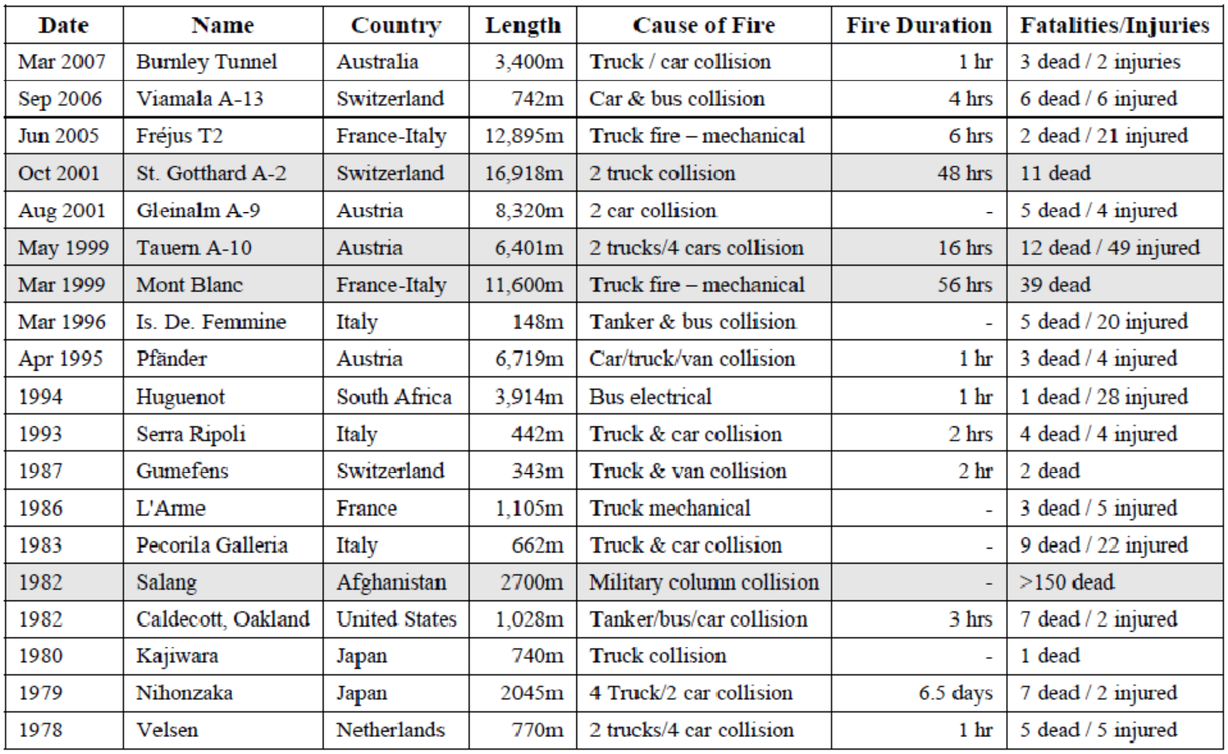
Accidental fires often happen in overcrowded environments such as workshops, warehouses or public areas. Tunnel fires in particular can easily aim to catastrophe due to a combination of factors: availability of high volume of flammable materials near ignition sources (because of overheating the vehicles brakes or engines), potential participation of many vehicles at the same time in a limited environment and flow of toxic gas and smoke from the fire. The potential consequences in terms of fatalities (of both users and rescue teams), as well as the economic loss related to property and damaged infrastructures (which may leads to long closure of the tunnel) must be considered. These consequences show the importance of doing a risk analysis and also the implementation of a well-designed prevention and protection measures and also put emphasis on development of adequate emergency procedures [12]. In the last decades, computer simulation of fire has become an impressive way for predicting and preparing rescue and suppression works.

Fire Research and Fire Engineering have grown due to continuous progress of Computational Fluid Dynamics (CFD), both in the field of theoretical modeling of physical phenomena and technological implementation of these models using complex methods and algorithms, and increasing computational power of modern computers and computing infrastructures [13].

In this study, from the engineering point of view, a vehicle fire has been simulated in Resalat tunnel of Tehran using FDS solver to analyze whether the available fire protection systems of tunnel is appropriate or not? The next step was reviewing of NFPA 502 for recommendations. At the end, sprinkler & water mist system have been chosen for simulating to evaluate their performance in case of fire.

2. Overview of Tunnel Fires

Fires in road tunnels are rare events, but when they happen, they may have catastrophic consequences both with respect to human life and material losses (vehicles and tunnel infrastructure). Recent examples of catastrophic road tunnel fires include the Mont Blanc tunnel (1999) with 39 deaths, Tauern tunnel (1999) with 12 deaths, and St. Gotthard tunnel (2001) with 11 deaths. Some of road tunnel fires during the last 30 years are listed in table 1. The risk of road tunnel fires is gradually increasing because of traffic growth, growing number of tunnels and tunnel lengths, and vandalism and tunnel fires can be very intense. Modern vehicles may reach flashover conditions in a few minutes. The limited vertical space in tunnels may let the fire to spread from one vehicle to another. The smoke from the fires may be pulled down by cold tunnel walls and re-circulated back to the fire, reducing visibility and possibilities for safe escape. Fires involving multiple vehicles, if unsuppressed, may go on for hours if not days [17].



Date	Name	Country	Length	Cause of Fire	Fire Duration	Fatalities/Injuries
Mar 2007	Burnley Tunnel	Australia	3,400m	Truck / car collision	1 hr	3 dead / 2 injuries
Sep 2006	Viamala A-13	Switzerland	742m	Car & bus collision	4 hrs	6 dead / 6 injured
Jun 2005	Fréjus T2	France-Italy	12,895m	Truck fire – mechanical	6 hrs	2 dead / 21 injured
Oct 2001	St. Gotthard A-2	Switzerland	16,918m	2 truck collision	48 hrs	11 dead
Aug 2001	Gleinalm A-9	Austria	8,320m	2 car collision	-	5 dead / 4 injured
May 1999	Tauern A-10	Austria	6,401m	2 trucks/4 cars collision	16 hrs	12 dead / 49 injured
Mar 1999	Mont Blanc	France-Italy	11,600m	Truck fire – mechanical	56 hrs	39 dead
Mar 1996	Is. De. Femmine	Italy	148m	Tanker & bus collision	-	5 dead / 20 injured
Apr 1995	Pfänder	Austria	6,719m	Car/truck/van collision	1 hr	3 dead / 4 injured
1994	Huguenot	South Africa	3,914m	Bus electrical	1 hr	1 dead / 28 injured
1993	Serra Ripoli	Italy	442m	Truck & car collision	2 hrs	4 dead / 4 injured
1987	Gumefens	Switzerland	343m	Truck & van collision	2 hr	2 dead
1986	L'Arme	France	1,105m	Truck mechanical	-	3 dead / 5 injured
1983	Pecorila Galleria	Italy	662m	Truck & car collision	-	9 dead / 22 injured
1982	Salang	Afghanistan	2700m	Military column collision	-	>150 dead
1982	Caldecott, Oakland	United States	1,028m	Tanker/bus/car collision	3 hrs	7 dead / 2 injured
1980	Kajiwara	Japan	740m	Truck collision	-	1 dead
1979	Nihonzaka	Japan	2045m	4 Truck/2 car collision	6.5 days	7 dead / 2 injured
1978	Velsen	Netherlands	770m	2 trucks/4 car collision	1 hr	5 dead / 5 injured

Table 1: Some of road tunnel fires during the last 30 years [8]

Because of the significant risk due to fires in tunnels, much effort has been put in understanding tunnel fires, their consequences, and importantly ways to mitigate the consequences. The first European research effort was the EUREKA 499 project which involved eight European countries. The project provided the first systematic evidence for the extreme heat release rates (estimated to be above 100 MW) that were possible due to vehicle fires in tunnels, especially when the case is HGV (heavy goods vehicle) fires or solid fire loads. Later, similar tests have been conducted in the Mont Blanc tunnel, in the Second Benelux tunnel, and in Runehamar test tunnel, where the highest peak HRR (heat release rate) values of about 200 MW for solid HGV fire loads were reported [17].

Due to the high cost of large-scale tunnel experiments, experimental research has also been carried out in model scale tunnels. Furthermore, there have been a few attempts to perform detailed CFD simulations on tunnel fire and fire suppression experiments [17].

3. Overview of Resalat Tunnel

3.1. General

Tehran, with population of more than 10 million, is one of the most crowded cities in the world and Resalat tunnel as one of its major routes, is located at the center of the city. The two-way-asphalted Resalat tunnel with 900m length was constructed in 2006. It joins Resalat highway from east to Hakim highway in west (figure 1). There is always a traffic jam in peak hours in the tunnel.

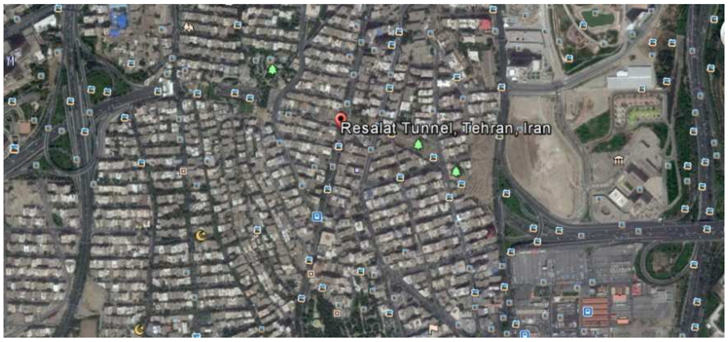


Figure 1: Plan of Resalat Tunnel

3.2. Fire Alarm System

In Tehran Resalat Tunnel, linear sensor heat detectors as well as CCTV detectors have been considered for fire alarm system. Also, manual call points were installed every 100m through the tunnel in order to inform the operator of the control room manually by drivers of any probable fire event in case the detection system is out of order. Sensor cables are combined with heat detectors which have been installed through the tunnel in order to measure both absolute temperature and rate of temperature rise. The sensor cable is capable of operating between -40 ºC to +85 ºC. Also, aggressive exhaust fumes, salts, humidity and fog, dust and dirt, as well as vibration would not influence the function of the fire detection system [14].

3.3. Fire Fighting System

Resalat tunnel has been equipped with standpipe system. There are fire hose boxes every 25 meters (38 sets in total) in one side of tunnel including hose reel and manual extinguishers.

4. Fire Simulation in Resalat Tunnel

4.1. Modeling approach

The Fire Dynamics Simulator (FDS), developed at NIST, is a CFD model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for the low-speed, thermally-driven flow concentrating on the smoke and heat transport from fires. FDS model solves the equations for the conservation mass, species, and momentum, considering conductive and radiative heat fluxes. The overall computation is treated as a Large Eddy Simulation (LES). The geometry of the domain, mesh resolution, obstacles, boundary conditions, material properties and different simulations parameters are all the simulation inputs [12].

4.2. Model of Fire in Resalat Tunnel

Tunnel fire experiments are often based on a specific test condition such as air velocity, geometry or tunnel slope which may be different from the design conditions of an actual tunnel project. The capability of the Fire Dynamics Simulator (FDS) to reproduce the consequences of pool fires in confined environments, such as those in road tunnels, has been tested. The use of computational fluid dynamics (CFD) in this field can be useful especially for the development of fire protection systems and for designing appropriate ventilation systems and escape routes [12].

When a fire happens in tunnel, the longer the distance between the fire origin and the exit, the more difficult it is for firemen to rush to save lives. So evacuation of the tunnel would be very dangerous if fire occurs in the middle of tunnel [15]. The modeling was done based on special conditions: east to west part of tunnel was chosen as the simulation object (figure 2 & 3); The length of the tunnel was reduced to 100 m in the middle of tunnel, with 13.5m width and 9m height; Neither the sloping nor the curvature of the tunnel has been considered; The ceiling and the side walls were considered to be built by non-flammable concrete. For the sake of more simple simulation, it has been supposed that everything is non-flammable except the fire origin (x=15.0m, middle of tunnel); Also the 6 jet fans installed in computational domain have been modeled.

Figure 4 shows the overall structure of the FDS model for the Resalat tunnel.

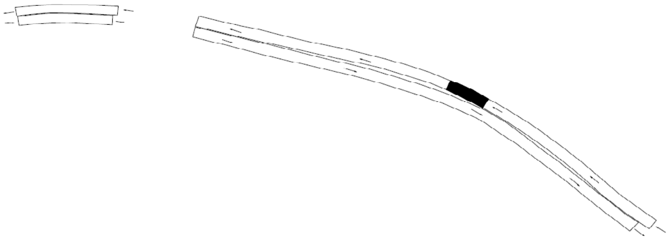


Figure 2: Plan of Resalat Tunnel (the black portion is the computational domain)

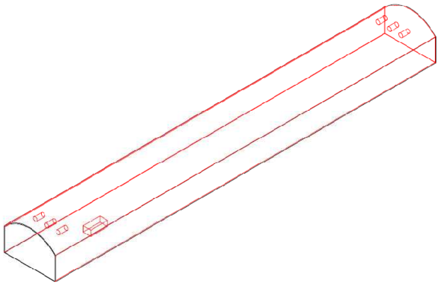


Figure 3: Sketch of the computational domain

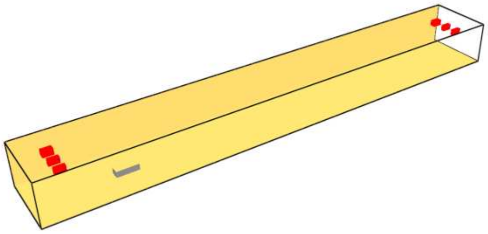


Figure 4: Schematic view of tunnel in SMV

And modeling conditions are as table 2:

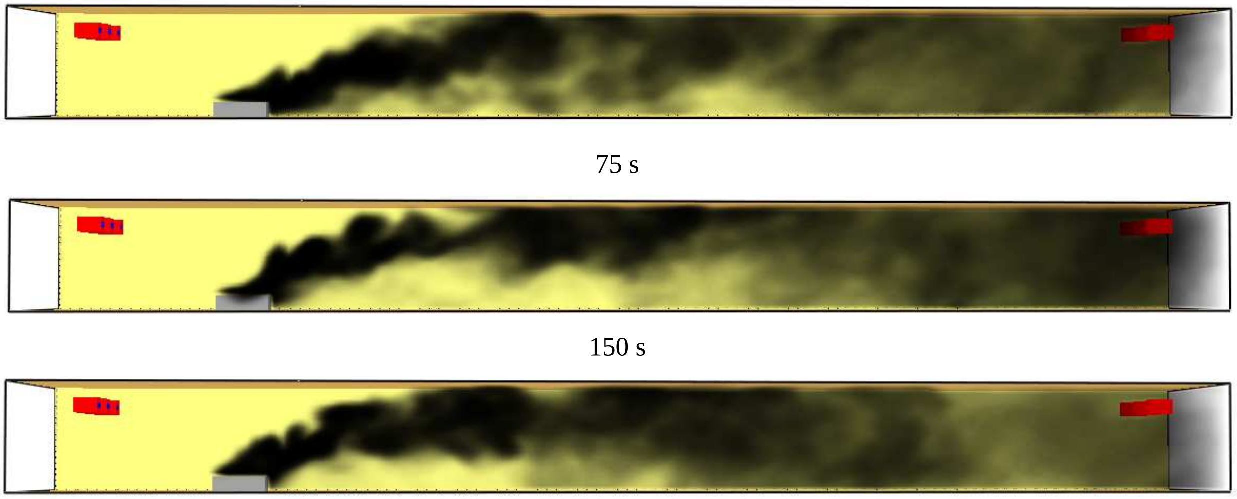
Tunnel Dimension	100m x 13.5m x 9.0m
Vehicle Dimension	4.4m x 2m x 1.4m
Flow Rate of Jet Fans	33.3 m^3/s [14]
Fire Heat Release Rate	10 MW [2]

Table 2: Tunnel fire modeling conditions

4.3. Results

The computational domain was divided into three 3D computational meshes with the 40 cm mesh density that has been chosen for the feasibility analysis [16] on which the fire was resolved. The mesh parameters fulfilled the conditions associated with efficient calculation of the FDS pressure solver. The total computational time was 300 seconds (figure 5 & 6).

35 s

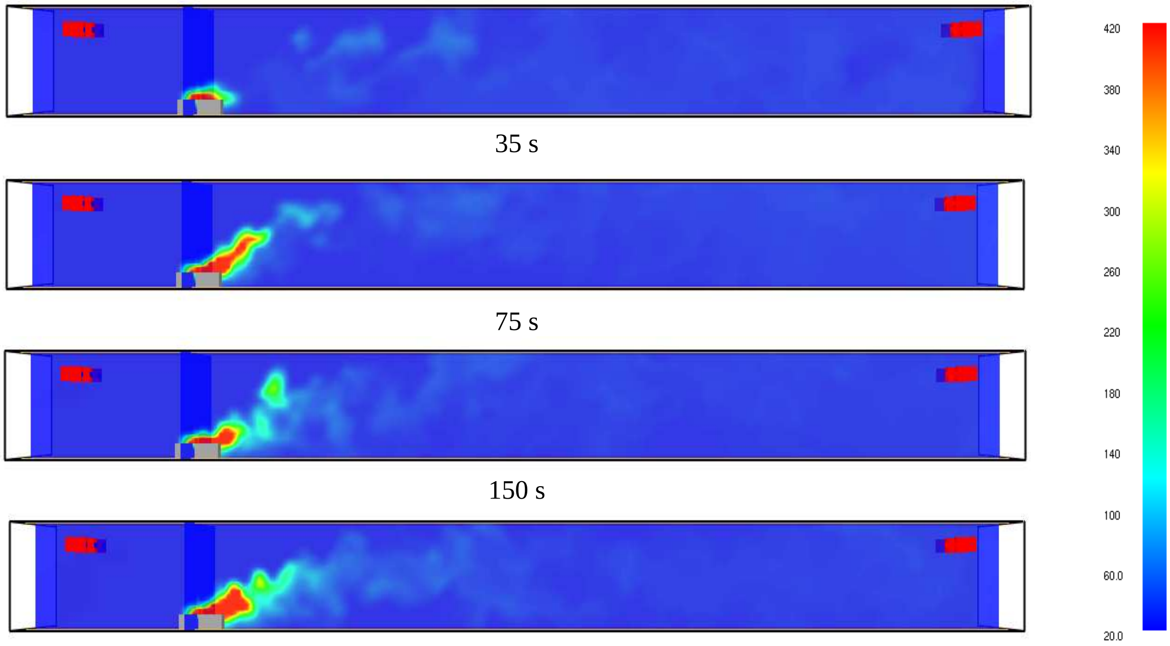


75 s

150 s

300 s

Figure 5: Smoke development at the 35th, 75th, 150th and 300th second of fire



35 s

75 s

150 s

300 s

Figure 6: Temperature contour at the 35th, 75th, 150th and 300th second of fire

4.4. Main Question

Regarding to simulation results, the temperature near the burning car will reach 130°C in 5 minutes. But according to NFPA 502, motorists should not be exposed to maximum air temperatures that exceed 60°C (140°F) during emergencies. It is anticipated that an air temperature of 60°C (140°F) places a physiological burden on some motorists, but the exposure also is anticipated to be brief and to produce no lasting harmful effects.

So the main question is "would it be enough to have just standpipe system to protect motorists from fire? What about fixed fire fighting system?"

To find the answer, first we check NFPA 502 for obligations and recommendations, and then sprinkler & water mist system will be simulated in tunnel to evaluate their effectiveness in case of fire.

5. Review of NFPA 502

Regarding to review of NFPA 502 from 2001 to 2014 edition, we found that there are significant changes in fire protection systems. Table 3 contains the collected paragraphs that relate to fire protection system.

2001	**4.3.1.** (8) Built-in fire protection features, such as the following: (a) Fire alarm systems (b) Standpipe systems (c) Sprinkler systems (d) Ventilation systems	**7.2 Road Tunnel Length.** For the purpose of this standard, tunnel length shall dictate the minimum fire protection requirements as follows: (1) Where tunnel length is less than 90 m (300 ft), the provisions of this standard shall not apply. (2) Where tunnel length is 90m (300 ft) or greater, standpipe systems and traffic control systems shall be installed in accordance with the requirements of Chapter 9 and Section 7.5, respectively. (3) Where tunnel length equals or exceeds 240 m (800 ft) and where the maximum distance from any point within the tunnel to an area of safety exceeds 120m (400 ft), all provisions of this standard shall apply. (4) Where the tunnel length equals or exceeds 300 m (1000 ft) all provisions of this standard shall apply.
2004	same as 2001 edition	same as 2001 edition
2008	same as 2001 edition	**7.2 Road Tunnel** Application. For the purpose of this standard, tunnel length shall dictate the minimum fire protection requirements, as shown in Table 7.2 and as follows: (1) Category X — Where tunnel length is less than 90 m (300 ft), the provisions of this standard shall not apply. (2) Category A — Where tunnel length is 90 m (300 ft) or greater, standpipe systems and traffic control systems shall be installed in accordance with the requirements of Chapter 9 and Section 7.6, respectively. (3) Category B—Where tunnel length equals or exceeds 240m (800 ft) and where the maximum distance from any point within the tunnel to a point of safety exceeds 120m (400 ft), all provisions of this standard shall apply. (4) Category C—Where the tunnel length equals or exceeds 300 m (1000 ft), all provisions of this standard shall apply unless noted otherwise in this document. (5) Category D — Where the tunnel length equals or exceeds 1000 m (3280 ft), all provisions of this standard shall apply. **Table 7.2** Fixed fire suppression system is a Not mandatory requirement for all above categories.
2011	**4.3.1.** (8) Built-in fire protection features, such as the following: (a) Fire alarm and detection systems (b) Standpipe systems (c) Water-based fire-fighting systems (d) Ventilation systems (e) Emergency communications systems	**7.2 Road Tunnel** Application. For the purpose of this standard, tunnel length shall dictate the minimum fire protection requirements, as shown in Table 7.2 and as follows: (1) Category X — Where tunnel length is less than 90 m (300 ft), the provisions of this standard shall not apply. (2) Category A — Where tunnel length is 90 m (300 ft) or greater, standpipe systems and traffic control systems shall be installed in accordance with the requirements of Chapter 9 and Section 7.6, respectively. (3) Category B—Where tunnel length equals or exceeds 240m (800 ft) and where the maximum distance from any point within the tunnel to a point of safety exceeds 120m (400 ft), all provisions of this standard shall apply. (4) Category C—Where the tunnel length equals or exceeds 300 m (1000 ft), all provisions of this standard shall apply unless noted otherwise in this document. (5) Category D — Where the tunnel length equals or exceeds 1000 m (3280 ft), all provisions of this standard shall apply. **Table 7.2** Fixed fire suppression system is a Not mandatory requirement for all above categories except D category that is conditionally mandatory requirement.
2014	same as 2011 edition	**7.2 Road Tunnel** same as 2011 edition **Table A.7.2** Fixed fire suppression system is a Not mandatory requirement for all above categories except C & D that are conditionally mandatory requirement.

Table 3: comparative table of NFPA502 from 2001 to 2014 edition (continued)

2001	**D.3 Background** No European country currently uses sprinklers on a regular basis. In some tunnels in Europe, sprinklers have been used for special purposes. In Japan, sprinklers are used in long or heavily trafficked tunnels. In the United States, only a few tunnels carrying hazardous cargo have some form of sprinkler system.	**D.3.1** Currently, the use and effectiveness of sprinklers in road tunnels are not universally accepted.
2004	same as 2001 edition	same as 2001 edition
2008	**Annex E** **Water-Based Fixed Fire-Fighting Systems in Road Tunnels** Examples of water-based fixed fire-fighting systems include sprinkler systems, deluge systems, mist systems, and foam systems. No European country currently installs fixed fire-fighting systems in road tunnels on a regular basis. In some road tunnels in Europe, fixed fire suppression systems have been used for special purposes. Catastrophic road tunnel fires have encouraged a re-evaluation of these systems for use in future road tunnels in Europe.	
2011	**Chapter 9 Water-Based Fire-Fighting Systems** 9.1.2 When water-based fire-fighting systems are installed in road tunnels, the fixed water-based fire-fighting system shall be installed, inspected, and maintained in accordance with NFPA 11, NFPA 13, NFPA 15, NFPA 16, NFPA 18, NFPA 25, and NFPA 750 or other equivalent international standards.	
2014	**same as 2011 edition**	

Table 3: comparative table of NFPA502 from 2001 to 2014 edition (continued)

Regarding paragraphs in Table 3, there are not significant changes from 2001 to 2008 but the big change begins after 2008. Up to 2008, the use and effectiveness of sprinklers in road tunnels are not universally accepted. But in 2008 the committee changed its mind about sprinkler system and catastrophic road tunnel fires have encouraged a re-evaluation of this system for use in future road tunnels. In 2008 edition it has been recommended to use sprinkler system but with some considerations [4]. We found more changes in 2011 edition; the term “sprinkler system” has been replaced with “Water-Based Fire-Fighting Systems” which included foam system, sprinkler system, water spray system, and water mist system. Also it has been listed the benefits of above mentioned systems in 2011 and 2014 editions [1, 3].

Since the construction of Resalat tunnel dates back to 2006, using of standpipe system at that time was appropriate, but according to 2014 edition of NFPA 502, fixed fire fighting system usage is a conditionally mandatory requirement. So in next section sprinkler as a traditional system and water mist as a new one will be simulated to evaluate their effectiveness in case of fire.

2001	**D.3.2** The major concerns expressed by tunnel designers and engineers worldwide (authorities) regarding fire sprinkler use and effectiveness include the following: 1. Fire is inside engine compartments and sprinkler may not affect. 2. Superheated steam made from water droplets may injure people. 3. Tunnel conditions (length, slope, ventilation) may affect sprinkler performance. 4. Activation of sprinklers far from fire because of smoke stratification may disturb smoke layer. 5. Water spraying from the ceiling of a subaqueous tunnel could suggest tunnel failure and panic in motorists. 6. Delamination of the smoke layer and induce turbulence and mixing of the air and smoke. 7. Testing of a fire sprinkler system on a periodic basis to determine its state of readiness is impractical and costly.	**D.3.3** Because of the concerns detailed in D.3.2, the use of sprinklers in road tunnels generally is not recommended.
2004	same as 2001 edition	same as 2001 edition
2008	**D.3.2** Listed below are the major concerns expressed in the past by tunnel designers, engineers, and authorities worldwide regarding the use and effectiveness of water-based fixed firefighting systems in road tunnels, along with the current assessment of those issues. 1. Fire is inside engine compartments and sprinkler may not affect. (purpose of a water-based fixed fire-fighting system is not to extinguish the fire but to prevent fire spread to other vehicles) 2. Superheated steam made from water droplets may injure people. (Fire tests have shown this concern not to be valid) 3. Tunnel conditions (length, slope, ventilation) may affect sprinkler performance. (Advances in fire detection technology have made it possible to pinpoint the location of a fire in a tunnel with sufficient accuracy to operate a zoned water-based fixed fire-fighting system.) 4. Activation of sprinklers far from fire because of smoke stratification may disturb smoke layer.(Independent laboratories have commented that they do not observe smoke stratification.) 5. Water spraying from the ceiling of a subaqueous tunnel could suggest tunnel failure and panic in motorists.(This theoretical concern was not borne out in practice. In the event of fire, motorists are likely to recognize water spraying from nozzles as a fire safety measure.) 6. Delamination of the smoke layer and induce turbulence and mixing of the air and smoke. (This has been shown not to be a valid concern.) 7. Testing of a fire sprinkler system on a periodic basis to determine its state of readiness is impractical and costly. (During routine testing, the system can be configured to discharge flow to the drainage system.)	**E.4 Recommendations.** The installation of water-based fixed firefighting systems should be considered where an engineering analysis demonstrates that the level of safety can be equal to or exceeded by the use of water-based fixed fire-fighting systems and is a part of an integrated approach to the management of safety. The tunnel operator and the local fire department or authority having jurisdiction should consider the advantages and disadvantages of such systems as they apply to a particular tunnel installation. **E.4.2 System Operation.** To help ensure against accidental discharge: 1. Manually activated deluge system with an automatic release after a time delay. 2. Time delay should not exceed 3 minutes 3. using interval zoning in piping
2011	E.3.2 There is general agreement that, in many cases, the inclusion of water-based fire-fighting systems can act as a valuable component of the overall fire and life safety system in a tunnel. Some of the benefits include the following: 1. Minimizing fire spread. 2. Fire suppression and cooling. 3. Improved conditions for first responders. 4. Improved performance of ventilation systems. E.3.3 additional consequences: 1. Reduced stratification. 2. Testing and maintenance requirements.	same as 2011 edition
2014	same as 2011 edition	same as 2011 edition

Table 3: comparative table of NFPA502 from 2001 to 2014 edition

6. Modeling Sprinkler and Water Mist Systems in Resalat Tunnel

For a fire to survive, presence of the three elements of the fire triangle, oxygen, heat and combustible material is necessary. Elimination of any one of the mentioned elements can extinguish a fire. A traditional sprinkler system removes the heat element of the triangle whilst water mist removes both the heat and oxygen elements. To achieve this result, it disperses water through specially designed nozzles for this purpose at different working pressures. Explaining generally, the water droplet size decreases when system pressure increases which significantly increases the total surface area of the water droplets. It leads to production of a greater volume of steam, removing more energy from the fire [9, 10].

Water-mist fire-suppression systems have become an interesting field of investigation in recent years since bromine-based chemical agents (e.g., halons) were banned by international agreement in 1993. Water mist has many advantages in comparison with conventional sprinkler systems such as low toxicity and greater efficiency [7].

Over last 20 years, performance of fixed water-based fire fighting systems has been investigated through extensive full-scale fire testing and simulation of fire case has been done with CFD tools. The history of traditional sprinkler technology, over last 150 years, had made it possible to gather all experiences into a specified design and installation rules. But water mist systems represent a more recent development for water based fire suppression technology. Although in the 20-year experience of water mist systems a large number of experimental works has been done, But according to short history of water mist system, no general design and installation rules have been emerged [17].

6.1. Inputs

Nozzles were modeled considering their operating pressures, experimentally determined flow rates and droplet size distributions. All input data have been listed in table 4.

	Sprinkler System	**Water mist System**
K-Factor (l/min/ bar$^{1/2}$)	80	4.3
Droplet Size (µm)	750	100
Nozzle Spacing (m)	3	3
Nozzle Quantity (Pcs)	12	12
Working Pressure (bar)	0.56 bar	80 bar
Flux (l/min/m2)	5	1.5
Duration (min)	5	5

Table 4: Input data to FDS solver for sprinkler and water mist systems [1, 11, 17]

6.2. Results

With respect to the results extracted from FDS solver, both systems reduce temperature of fire origin to 365°C (figure 9 and 10). Although activation of water mist system disturbs smoke layers more than sprinkler system (figure 7 & 8), but water mist system keeps fire around the origin and doesn’t allow migration of heated flow through the tunnel (figure 10). In case of activation of sprinkler system according to figure 10, an air flow with 90°C moves through the tunnel that may injure escaping people.

Also diagram 1 shows 87.96% reduction in HRR growth with sprinkler system against 88.68% in case of water mist system activation in 5 minutes.

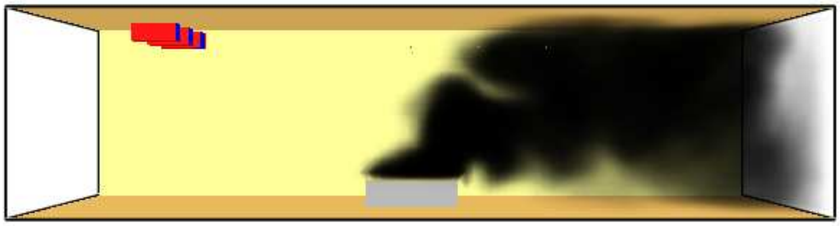


Figure 7: Smoke development with sprinkler system

Figure 8: Smoke development with water mist system

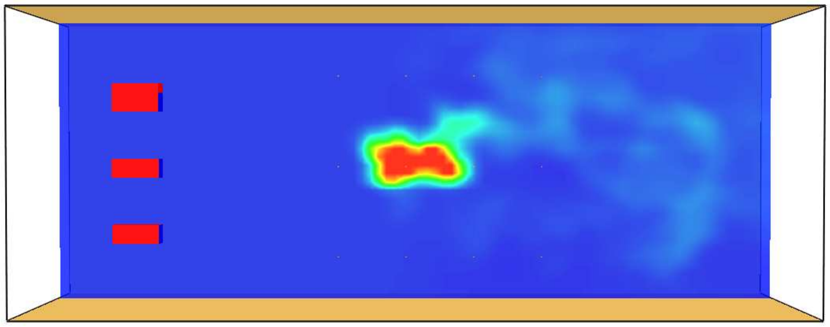


Figure 9: Snapshot of fire with sprinkler system in Z=1.6 m

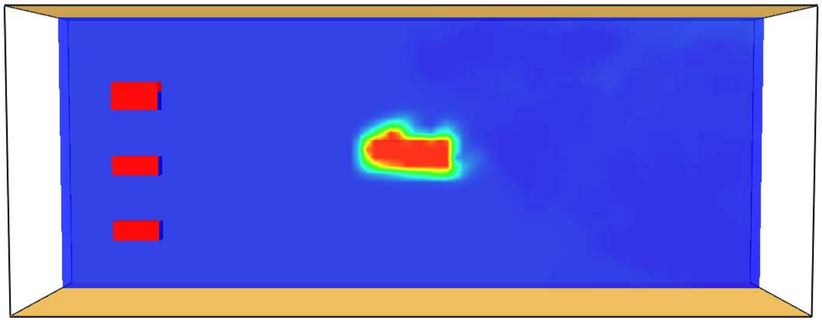
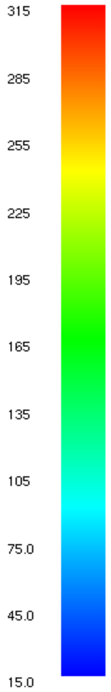


Figure 10: Snapshot of fire with watermist system in Z=1.6 m



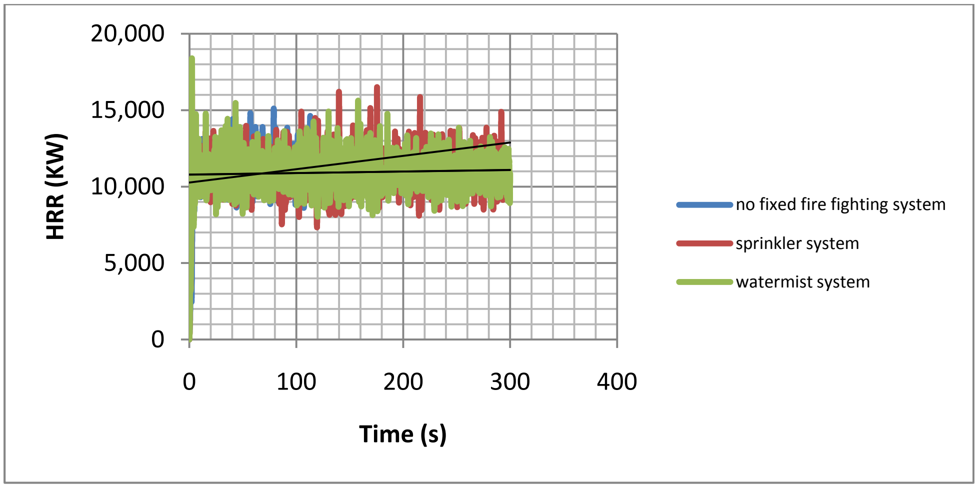


Diagram 1: Comparison of HRR growth in 3 scenarios

7. Conclusion

In this paper, to evaluate current fire fighting system of Resalat tunnel, we modeled a vehicular fire in the middle of the tunnel. Results showed that in less than 5 minutes, temperature around the fire origin will reach to 130°C that is much more than the maximum temperature mentioned in NFPA 502. Review of NFPA 502 from 2001 to 2014 edition and the result was that there has been an optimistic view about fixed fire fighting systems from 2008 on.

Then again CFD code FDS has been used to model sprinkler and water mist systems in Resalat tunnel; for these conditions, it was found that although water mist system disturbs the smoke layers more than sprinkler system, but it can keep fire from spreading to other vehicles and prevent migration of hot airflow through the tunnel.

In summary, there is a requirement to improve the fire fighting system of Resalat tunnel in compliance with 2014 edition of NFPA 502.

Acknowledgment

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References

[1] NFPA 750, Standard on the installation of water mist fire protection systems, National Fire Protection Association, 2013.
[2] NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, National Fire Protection Association, 2014.
[3] NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, National Fire Protection Association, 2011.
[4] NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, National Fire Protection Association, 2008.
[5] NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, National Fire Protection Association, 2004.
[6] NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, National Fire Protection Association, 2001.
[7] F. Nmira, J.L. Consalvi, A. Kaiss, A.C. Fernandez-Pello, B. Porterie, A numerical study of water mist mitigation of tunnel fires. *Fire Safety Journal 44 (2009) 198–211*
[8] I.J. Duckworth, Fires in vehicular tunnels, *12th U.S./North American Mine Ventilation Symposium 2008;* 393-400
[9] British Automatic fire sprinkler association ltd, Technical Guidance Note Watermist Systems, *Issue No 1: February 2012 ISBN 0-9552628-9-5; 1-20*
[10] European Commission, Work Package 2 of the Research Project UPTUN, *August 2007; 1-37*
[11] NIST. Fire Dynamics Simulator User's Guide. *2013.*
[12] M. Derudi, S. Tavelli, A. Frassoldati, A. Cuoci, CFD Modeling of Road Tunnel Fires, *XXXV Meeting of the Italian Section of the Combustion Institute: 2012; 1-6*
[13] L. Hluchy, L. Halada, P. Weisenpacher, J. Glasa, V. Sipkova, V. Tran, Tunnel Fire Simulation using FDS (Fire Dynamics Simulator), *EGI Community Forum 2012 / EMI Second Technical Conference, Munich, Germany, 26-30 March, 2012*
[14] N. Modiri, Z. Noferesti, Tehran Resalat Tunnel Innovations, *5th International Conference 'Tunnel Safety and Ventilation', Graz, 2010; 93-100*
[15] D. Yan-li, M. Xiao, Z. Shu-min, Study on Feasibility of Automatic Sprinkler System Applied in Underground Tunnel, *Procedia Engineering 52 (2013) 79 – 87*
[16] I. Vermesi, F. Colella, G. Rein, G. Jomaas, The Feasibility of Multiscale Modeling of Tunnel Fires Using FDS 6
[17] J. Vaari, S. Hostikka, T. Sikanen, A. Paajanen, Numerical simulations on the performance of water-based fire suppressions systems, *2012, Julkaisija – Utgivare – Publisher, Finland*