Study on the Effectiveness of Sprinklers in Tunnels

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Abstract — **The required water flow for adequate deluge system operation in tunnels is currently only prescribed by few regulatory authorities having jurisdiction. There is scarce information on the amount of water required for correctly suppressing a car fire and the threshold by which the systems fails be effective. This paper aims at bridging this gap in tunnel fire suppression knowledge; the effectiveness of deluge sprinkler systems was investigated by performing a series of full-scale car fire experiments. These experiments were performed by placing a single car under a deluge nozzle; setting the car on fire and carefully gauging the burning behavior of the car fire. Temperatures inside, around and above the car were measured and infrared camera footage was used to derive flame heights. Results from this study yielded two forms of car fire suppression by deluge system: *gradual* and *instantaneous*. A relationship between the heat release rate of a fire and the required water flow for the deluge system is presented. Moreover, it was found that a water flow of 6.6 mm/min is effective at reducing the temperature in the immediate vicinity of the car for a wide range of fire sizes.**

Keywords — car fire, tunnel fire, suppression systems, deluge, heat release rate.

I. INTRODUCTION & BACKGROUND

Increasing urbanization and population growth drives the need for more efficient transportation solutions. In the past decades the world has become more connected through means of communication and mobility. At the same time, environmental and geographical constraints challenge the way transportation evolves. As a way to overcome these hurdles in an efficient manner, tunnels are becoming more present in modern infrastructure developments.

The efficient and elegant mobility solution of a tunnel presents numerous fire safety considerations that must be addressed. Deluge sprinkler systems, characterized by yielding large water flows and big droplet sizes, are the most common Fixed Fire Fighting System (FFFS) used in tunnel applications; however, there seems to be no general consensus on their quantifiable effectiveness. The required water flow rate to suppress a tunnel fire remains unclear and, consequently, there is a huge potential benefit from optimizing a costly installation, maintenance, and drainage of deluge systems.

Currently, there are two countries that have a prescribed design guideline for deluge systems in their tunnels as general practice: Japan and Australia. Japan prescribes a water flow of 6 mm/min [1] whereas the Australian requirement is 10 mm/min [2]. The substantial difference between these requirements expresses the uncertainty of underlying fire science. In countries where there is a lack of prescriptive framework regarding deluge systems in tunnels, often, a more conservative water flow is applied.

Within the scope of the work presented, the least onerous tunnel fire scenario is simulated, hence the absolute minimum required water flow is derived. The aim of this work is to quantify the performance of a deluge system in car tunnels and, consequently, provide information for the explicit optimization of these, otherwise suboptimal systems.

II. METHODOLOGY

A. Experimental Setup

The experimental setup consisted out of a single deluge sprinkler nozzle symmetrically aligned above a car. A steel frame was constructed in order to position the nozzle at a height of 5.5m from the ground, as shown in Figure 1.
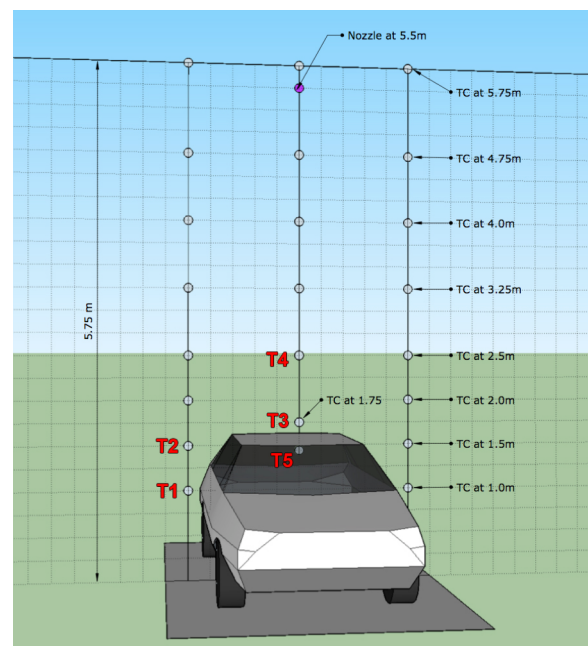

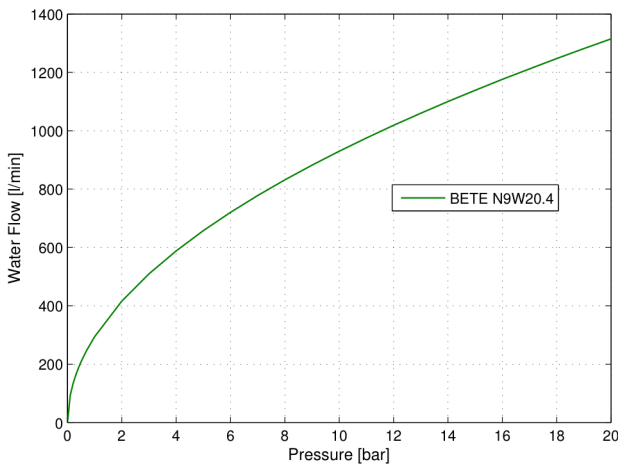*Figure 1: Schematic of the Test Setup*

Figure 2: Pressure - Water Flow Relationship

B. Instrumentation

1) Thermocouples

Three thermocouple trees were placed: one at the center and one at both sides of the car. The distribution of thermocouples is shown in Figure 1. The thermocouple tree at the center allowed for flame height estimation and assessment of fire severity at the target surface of a tunnel lining. The main objective of the thermocouple trees at the sides was to determine the risk for fire spread before and after sprinkler activation.

Additionally, four thermocouples were placed inside the car: one under the roof, one between the front seats, one in the middle of the rear foot compartment and one in the middle of the backseat, respectively.

2) Video and Infrared Cameras

Video and Infrared cameras were used throughout the tests. The video cameras enabled understanding the different stages of the burning behavior and helped with estimating the flame heights as long as there was sufficient visibility. When visibility was lost, the IR camera was the sole source of valuable footage. Based on this footage the flame heights can be determined and, consequently, the heat release rate can be estimated.

C. Water Distribution

A BETE nozzle type N9W20.4 was used in a single-nozzle configuration as explained above. The water flow from the nozzle was directly controlled by regulating the system's water pressure. This relationship is expressed in equation (1).

$$FlowRate = K * \sqrt{p} \qquad (1)$$

In this equation, p is the pressure in bar and K is the factor correlating the system pressure with the water flow. This K-factor of 294 is reported by the manufacturer. The flow rate relationship is shown in Figure 2 for the nozzle used in the experiments. This flow is distributed over an area with a coverage diameter D and is dependent on the system pressure, installation height and spray angle.

In reality there is no deluge nozzle that can evenly distribute the nozzle water flow over the covered area. In order to determine the distribution of the water flow at ground level, a series of standard 'pan tests' [3] were performed. During these tests, square pans were placed along the radius away from the sprinkler nozzle (See Figure 3). After a certain discharge time, the water flow at these discrete points away from the sprinkler head can be derived by measuring the height of water in each pan and dividing it by the discharge time.

The pan test shown in Figure 3 consists out of a strict procedure to ensure consistency. First, a plastic sheet is placed on the boxes while the system activates. In this manner, any distortion during ramp-up of the system pressure is avoided. After stabilization at the requested system pressure, the sheet is removed.

The square pans (with a surface area of 356 x 356 mm) collected dispersed water during a fix time-period after which the boxes were covered again and the water was turned off. The volume of water in each of the boxes was measured, divided by the surface area of the box, and divided by the time-period; hence the water distribution was quantified in [mm/min]. This process was repeated for a range of operational water pressures (See Figure 4).

In order to assess the radial symmetry of the water distribution, additional pan tests were performed for two pressures in 45° increments to cover the entire surface.

Figure 3: Setup of Water Distribution Test

D. Car Fire Tests

1) Ignition Source

A bag of woodchips drenched in diesel was used as the source of ignition. This ignition source was placed in the middle of the foot compartment of the backseat. This is not necessarily the most likely, but serves as a worst-case scenario.
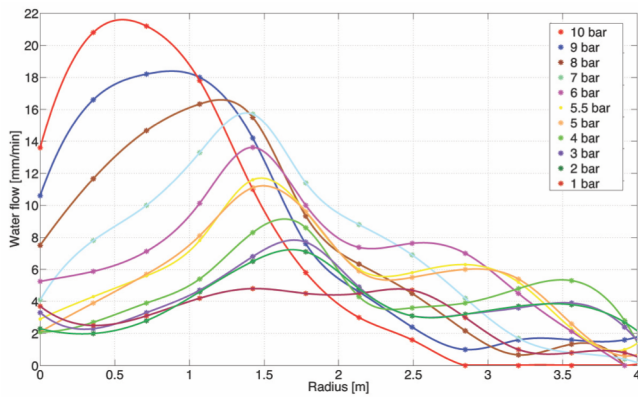
Figure 4: Water Distribution Away from the Deluge Nozzle

2) Fuel Load

The main fuel load in cars are the seats, interior lining, plastics in the finishing or the bodywork, the tires, and the fuel from the vehicle tank. The latter is not present for the purpose of this experiment. It is a possibility that the fire barrier between the engine and the passenger compartment fails. In that case, additional fuel from cabling and other combustibles from the engine compartment are added to the fuel load. The doors of the tested cars were removed prior to the test but placed inside the car to maintain the same fuel load.

3) Heat Release Rate

In order to estimate the HRR from the flame height from the burning car (See Figure 6), the mean flame height needs to be measured. This is required since the intermittent part of the flame fluctuates several times per second and an instantaneous analysis would therefore not resemble the heat release rate of the fire. The mean flame height is found by collecting the flame height of 100 infrared frames (4 seconds at 25 FPS) and developing a cumulative normal distribution. The mean flame height is the height that corresponds with a probability of 0.5.

The SFPE Handbook of Fire Protection Engineering [4] provides Heskestad's flame height correlation. This is the method used to derive heat release rates from the mean flame heights in this paper. This relationship is given in equation 3.2 where D [m] is the diameter of the fire and Q̇ is the heat release rate [kW].

$$L = 1.02D + 0.235Q^{2/5} \quad (2)$$

Rearranging this equation for the HRR gives:

$$\dot{Q} = \left(\frac{L+1.02D}{0.235}\right)^{5/2} \quad (3)$$

The flame length L [m] is derived from the IR camera recordings and the fire diameter D [m] is assumed to be the width of the car.

III. RESULTS

This section gives an overview of the most significant experimental results: the results from the water distribution tests are shown and the temperature measurement data shows how the fire is influenced by sprinkler activation. For the assessment of the burning behavior of the car, the main focus lies on thermocouples T1-T5 (See Figure 1). If the temperature in the immediate vicinity of the car can be reduced, it is assumed that a drop of at least this magnitude occurs further away from the burning vehicle; e.g. at the tunnel interface.

An instantaneous drop in temperature is defined as a drop to a constant temperature below 100°C during the 100s of sprinkler activation. A gradual drop is a drop that occurs over a longer period of time, i.e. a drop that hasn't yet reached a constant temperature below 100°C during activation. If one temperature drops slightly, but another one rises, the 'temperature in the immediate vicinity of the car' is assumed to rise.

A. Water Distribution

The variation of the water dispersion along the radius away from the sprinkler nozzle is shown in Figure 4. A trend can be deduced: from a single peak for the highest system pressure towards a double water flow peak for lower pressures. The variation along the radius away from the nozzle confirms that the water distribution on the ground cannot be found by simply dividing the nozzle flow rate with the coverage area.

Note that Figure 4 gives the water distribution in one direction only. Two-dimensional water distribution tests were also performed within the scope of this work. In order to find the representative water flow for a certain system pressure it is assumed that a car fire is roughly equivalent to a pool fire with a diameter of 2 m. This means that the water flow values from Figure 4 must be integrated from the origin to the 1m radius mark. Since the integration of the water flows is carried out for a radius equal to unity, the resulting numerical value is the previously mentioned 'representative water flow' or simply the average water flow. The result of this integration is shown in Figure 5.

As can be seen from Figure 4, for the 0 to 1m radius interval, the water flow for 1 bar is in fact higher than that of 2 and 3 bar. One bar of system pressure is not enough to create a pressurized water umbrella with the same radius similar droplet size. As a consequence, there is a significantly larger amount of water falling closer to the centerline than is the case for 2 bar.
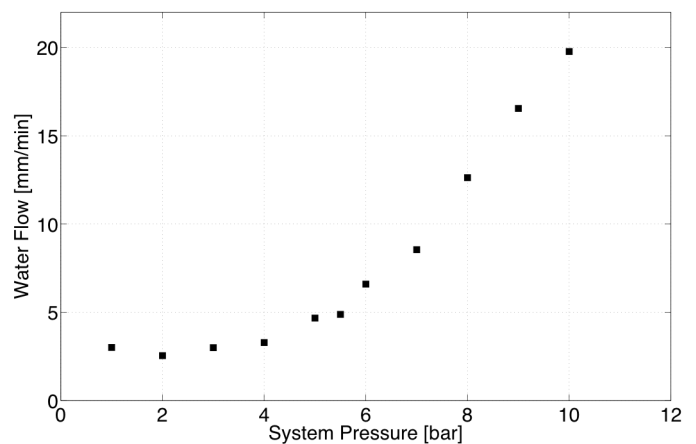

Figure 5: Representative Water Flow Rates for the Car Area

Figure 6: Typical car fire test (prior to activation of the suppression system)

B. Car Fire Tests

1) Test 1

Figure 7 shows the how the two deluge activations for Test 1 affected the temperatures in the immediate vicinity of the burning car. During the first activation of 2.5 mm/min there was no clear drop in temperatures throughout deluge activation. The temperature right next to the car rose significantly. The second activation, with 8.6 mm/min, showed a different sprinkler effect: during the 100s of deluge activation, the temperatures around the car have dropped to a uniform 50°C. The drop in temperature has occurred within these 100s and can therefore be assumed as an instantaneous drop.

2) Test 2

The first three deluge activations for Test 2 are shown in Figure 8 and three distinct sprinkler effects can be witnessed. The first activation of 3.3 mm/min shows how the temperature above the car kept rising. This effectively shows how the fire was not being contained inside the vehicle. It does however show that the temperatures right next to the car were kept well under 100°C. The second activation of 6.6 mm/min showed a

clear case of a gradual drop in temperature right above the car. The third activation of 8.6 mm/min however, showed an instantaneous drop in temperature. Interestingly, there was an initial rise in temperature right next to the car after deluge activation. This is likely to be linked with the downward momentum generated by the deluge system, initially pushing the flames down- and outwards.

3) Test 3

The first activation of 4.7 mm/min, shown in Figure 9, shows that the fire could not be controlled. The fire was able to grow throughout sprinkler activation. However, the deluge system managed to shield the thermocouples right next to the car from the heat. The second activation deployed the highest water flow tested (14.1 mm/min) and an instantaneous drop in temperature occurred within seconds.

4) Test 4

In the first activation of Test 4 (See Figure 10) previously determined trend was confirmed. For 4.7 mm/min, the deluge system managed to drop the temperatures around the car; effectively minimizing the risk for fire spread. However, a temperature rise occurred above the car during the 100s of deluge activation. The second activation of 14.1 mm/min showed a clear instantaneous drop in temperature.

5) Test 5

The first activation for Test 5 (See Figure 11) occurred as soon the flames connected over the roof of the car. At this point, the thermocouples did not yet heat up significantly. It can be seen from this activation that all temperatures in the vicinity of the car can be kept well below 100°C with 4.7 mm/min. From the same figure you can see T5 rose right under the roof. This shows that the fire is actively being contained inside the vehicle and underlines the importance of a small activation time. A gradual drop in temperature could be witnessed from the second activation of 8.6 mm/min whereas the third activation showed an instantaneous drop in temperatures. Note that there was an initial rise in temperature right next to the car.
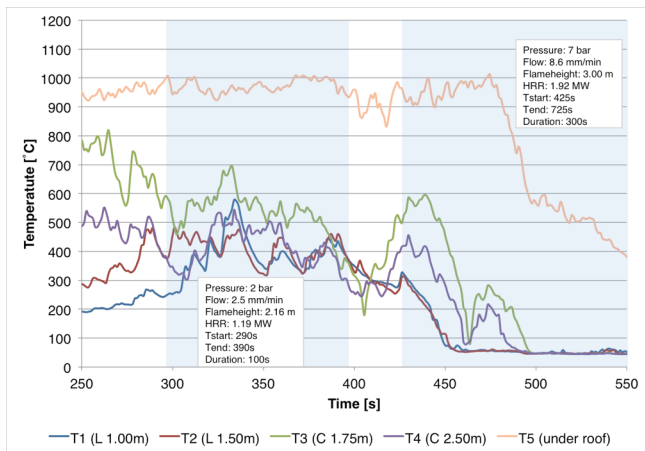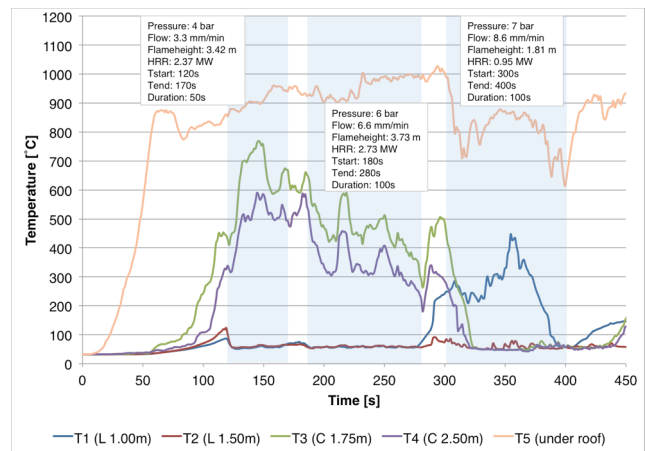

Figure 7: Temperatures in the vicinity of Test 1.

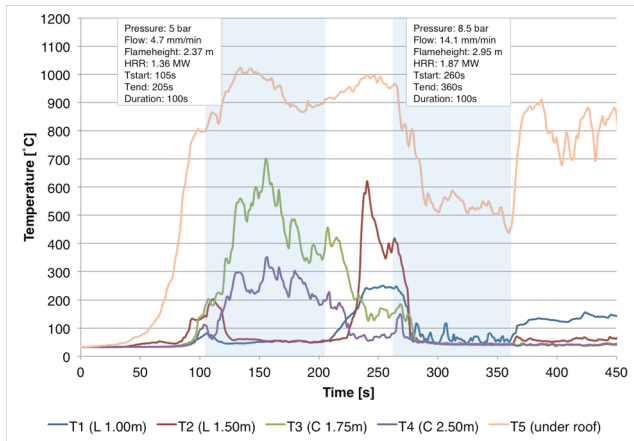*Figure 8: Temperatures in the vicinity of Test 2.*

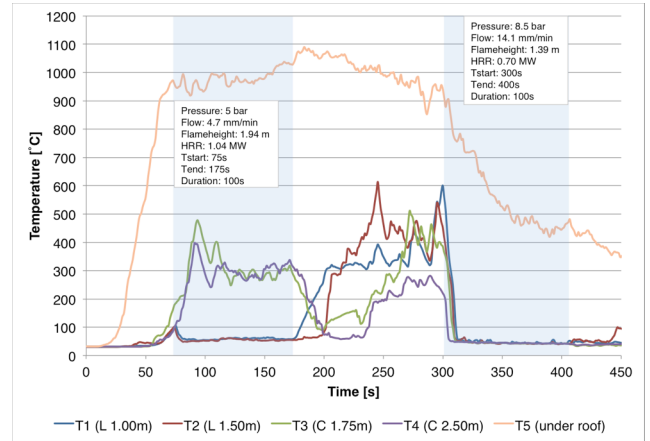*Figure 9: Temperatures in the vicinity of Test 3.*

Figure 10: Temperatures in the vicinity of Test 4.

Figure 11: Temperatures in the vicinity of Test 5.

IV. ANALYSIS AND DISCUSSION

A comprehensive suppression-effect classification is applied in the following section. A drop in temperature during the 100 seconds of sprinkler activation is divided in three main categories: a gradual drop in temperatures, an instantaneous drop in temperatures and a temperature rise after deluge activation. The former scenario is a drop that occurs steadily when the system is active. 'An instantaneous drop' is the scenario where the temperature reaches a constant temperature below 100°C within 100 seconds of sprinkler activation. This category is subdivided to include the effect of the steam pushing down the flame and making the temperature right next to the car rise before dropping instantaneously as well. Basically, this effect delays the instantaneous drop right next to the car. Lastly, there is the scenario where the temperature continues to rise. Figure 12 is the result of applying this classification on the experimental results.

The data points corresponding to the three main categories appear to roughly correspond with as many regions in Figure 12. However, the number of data points is insufficient to categorize the plot in three distinct regions. The transition from one sprinkler effect to another is therefore marked with shaded regions. The most conservative approach to these shaded areas is to assume that the 'worst' scenario would occur in this particular region i.e. a temperature rise in the horizontal shaded bar and a gradual rise in the diagonal region. The thresholds between these three regions cannot be determined more accurately than the shaded areas from the given set of data.

It is found that above 6.6 mm/min, the water flow is expected to drop the temperatures around a burning car. Whether this drop in temperature is instantaneous or gradual, depends on the water flow that is applied. Essentially, there are two ways of achieving an instantaneous drop in temperature: one is to increase the water flow, another is to keep the fire size small enough. The latter basically comes down to minimizing the activation time.
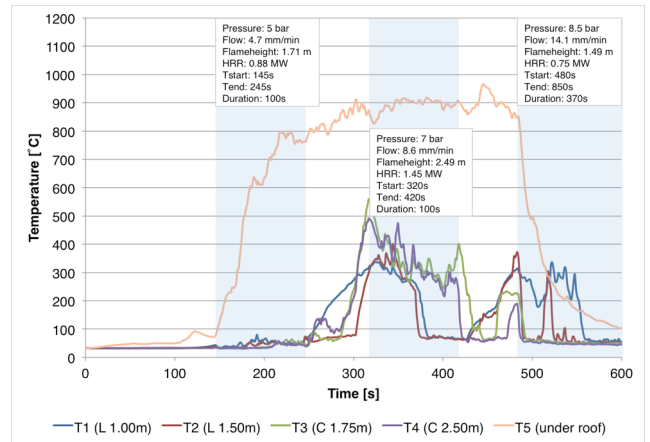
In the previous discussion, the temperatures around the car were assessed and led to a division of possible sprinkler effects. This is highly relevant for tunnel fire safety design; if one is to design a deluge system for a tunnel with a very high expected traffic density, eliminating the potential for fire spread basically comes down to dropping the temperatures in the immediate vicinity of the car. However, if the expected tunnel traffic density is not that high and the vehicle lanes are not particularly narrow, the fire spread to adjacent cars might be less relevant. In that case, one could design for keeping temperatures at the tunnel interface below a certain threshold.

V. CONCLUSION

A series of full-scale fire tests were conducted in order to assess the required deluge sprinkler water flow for suppression of car fires. It is found that sprinklers can effectively cool the area around a burning car. This shows that these systems can serve the purpose of limiting the fire to the initially involved vehicle and protect the tunnel structure if the right water flow is used.
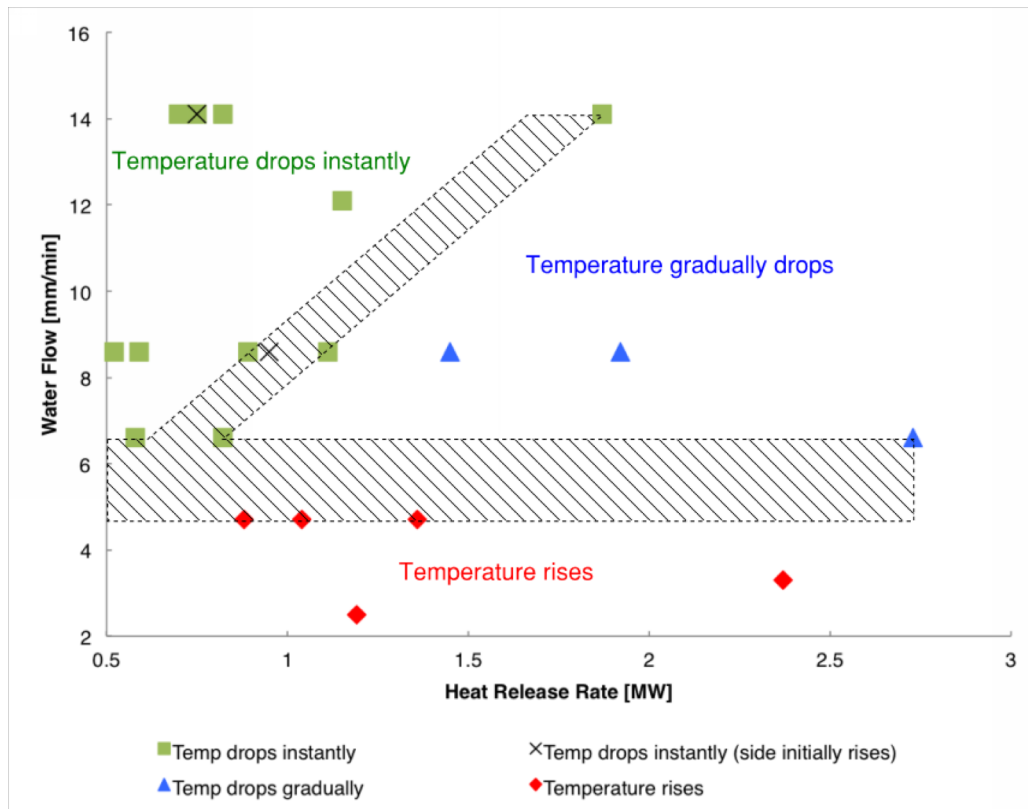
Figure 12: Graph of Sprinkler Effect

Three suppression regimes were identified: one where you have an instantaneous drop in temperatures around the car, another where this drop occurs gradually and lastly the scenario where the fire is not controlled and the temperatures keep rising. In some cases, where an instantaneous suppression occurred, the temperature right next to the car rose before eventually dropping sharply as well. This effect is likely to be linked with the water and steam generating a downward momentum and effectively pushing the flame down- and outwards.

It was found that there are two ways of achieving an instantaneous drop in temperature. One is to apply a sufficiently high water flow; another is to have a smaller fire size. The former would lead to a more conservative, expensive system whereas the latter basically comes down to minimizing the activation time. This emphasizes the importance of rapid deluge activation.

The boundaries between the three regimes depend on the flow of water that is applied. It was shown that a water flow in the order of 7 mm/min (6.6 mm/min) managed to drop the temperatures around a burning car. Below this water flow the fire is assumed to be out of control. It must be noted that these results are only valid for the exact configuration as tested, with no ventilation and for the given fire sizes.

Whether an instantaneous or a gradual drop in temperature is required, depends on the distance to an adjacent car. This directly relates to the expected traffic density and car lane width. The results presented in this paper can help in the design of deluge sprinkler systems in tunnels.

Future research must investigate the effects of the potential rise in temperature right next to the car following deluge activation. The thresholds between the different suppression regimes must be narrowed down by performing similar tests.

Additional analysis on scalability is required to investigate applicability on heavy goods vehicles. Lastly, the influence of droplet size and longitudinal ventilation must be looked into.

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