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**RESCUE OPERATIONS IN UNDERGROUND MASS TRANSPORT SYSTEMS AT FIRES AND DELIBERATE ATTACKS**

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**ABSTRACT**
Fire and rescue operations in mass transport systems underground often constitute a great challenge for the first responders. In rush-hour traffic at important junctions thousands of people can be located at a relatively small area. At underground fires or deliberate attacks in these premises the need for assistance or rescue can be extensive and the possibilities to reach those in distress are limited. In case of deliberate attacks with explosives the risk for a second delayed attack, aimed at the first responders, has to be considered. The blast load and structural response can destroy important functions, used for evacuation, in the metro carriage and harm passengers in the exposed and adjacent carriages. This can increase the need for assistance from the fire and rescue services. In this paper the possibilities for the first responders to assist and rescue persons at the event of fire or explosion in a tunnel is discussed, based on the research results from the full scale tests performed within the METRO-project.

**KEYWORDS:** Tunnel, fire, explosion, fire and rescue operation

**INTRODUCTION**
The work presented in this paper is a part of the METRO-project [1], a Swedish research project about infrastructure protection. The focus of the project is on the protection of underground rail mass transport systems, e.g. tunnels and subway stations. Both fire and explosion hazards are studied. METRO is a multidisciplinary project where researchers from different disciplines cooperate with practitioners with the common goal to make underground rail mass transport systems safer in the future.

The results from the full scale METRO fire and explosion tests are presented and analyzed from a fire and rescue perspective. The analyzes and assumptions in this paper are based on a normally equipped and manned “standard” BA-rescue team in Stockholm Greater Fire Brigade. The conditions at a fire, accident or arson, are compared with the conditions that can be expected at a deliberate attack with explosives. The difficulties are highlighted and recommendations regarding fire and rescue operations are made both in areas concerning tactical approaches, suggested solutions at the scene of the accident and future need for research and development.

Four different areas have been chosen to analyze more thoroughly:

1. The experiences from, and effect on, the BA - rescue unit, for example regarding temperature and sight.
2. How do the images of the fires turn out in the IR camera? How easy is it to identify potential victims using the IR-image camera? How did the rescue “robot” – ROV (remote operated vehicle) with the IR image camera work in this environment?
3. The experiences of the use of the mobile PPV-ventilator, from a fire and rescue perspective.
4. Which circumstances in the environment may influence a possible fire and rescue operation?
A fire and rescue operation inside a tunnel involves many difficulties that alone or in combination influence the outcome of the fire and rescue operation. A fire or explosion, or in worst cases a combination of the two, inside a train tunnel is a complex situation where many persons can be in need of assistance. Trains and metros carry many persons, with different possibilities to rescue themselves to a safe environment. An ageing population and increased demands for accessibility for disabled persons also represents a challenge for the fire and rescue services in case of a rescue operation. The evacuation route, the location for smoke extraction and the rescue services’ response route often co-exist in the tunnel tube. Long evacuation routes put more persons at risk if they are affected by the toxic smoke and fire and rescue operations with long response routes in high-risk environments make the transportation speed for the fire and rescue services slow if all safety measures are correctly addressed. Tunnel fire and rescue operations sometimes require special equipment that most fire and rescue services do not have access to.

BACKGROUND
In recent years a number of serious fires [2-7] have occurred in train tunnels. In some cases the consequences of these fires have been large in terms of loss of life and the accidents have shown the need of, but also the difficulties with, effective fire and rescue operations. In addition to the risk for injuries and fatalities fires in mass-transport systems will have a significant impact on the society since it decreases the confidence for the infrastructure itself. The economic losses not just strike the tunnel owner, the tunnel operator but also the public expenses and private interests.

At real life incidents or accidents the information about heat release rates (HRR), temperatures or toxicity only can be estimated based on the injuries and damages, investigated afterwards. The fire and rescue services can rarely relate their experiences to exact data and some phenomenon can not at all be paid attention to as the main aim is to save persons, property or the environment. Full scale fire tests are very expensive and demand a large organization. Few full scale fire tests have been performed and explosion tests, both in model and full scale, are often not public for security reasons. Full scale tests even more rarely include many disciplines and usually focus on strictly the fire dynamics or the effect of a specific fire technical installation, such as for example sprinkler or ventilation. Despite the expenses a few valuable full scale tests have been performed and contributed to the level on attainment worldwide [8-14]. Early tests did not include HRR measurements and many of them were based on pool fires, not vehicle fires. The possibilities for fire and rescue operation have seldom been investigated in the full scale tests and are first presented systematically in the Runehamar tests [15].

STRATEGY AND TACTICS AT FIRE AND RESCUE OPERATIONS IN TUNNELS
The IC can, with the help of the fire and rescue forces; either take an offensive strategy (fight the fire) or a defensive strategy (not fight the fire). This paper mainly discusses the circumstances where the aim is to fight the fire, but also try to identify the cases when this not is possible. In case of a deliberate attack with explosives, without a following fire, the strategy is offensive (rescue persons inside the tunnel) in most cases. Circumstances where the IC can make a decision to wait and see could be during risks for further explosions or if the construction first has to be reinforced to ensure a safe working environment for the first responders.

The experiences from the full scale fire tests are analyzed with respect to the five possible tactical approaches possible to use in case of a fire [16];

1. Fight the fire from inside the tunnel in order to save persons inside the tunnel.
2. Assist or rescue persons inside the tunnel and take them to a safe environment.
3. Control the air flow in the tunnel in order to save persons inside the tunnel or support the fire and rescue operation.
4. Fight the fire from a safe position to reduce the consequences of the fire.
5. Take care of persons that without assistance have rescued to a safe environment.

In case of an explosion the possible tactical approaches instead would be;

1. Secure the train and clear train and/or tunnel to make evacuation and rescue possible.
2. Assist or rescue persons inside the train or tunnel and take them to a safe environment.
3. Control the air flow in the tunnel in order to clear the tunnel from toxic gases and by this reduce the impact on persons inside the tunnel.
4. Take care of persons that without assistance have rescued to a safe environment.

In both cases the one or more of the tactical approaches can be applied in combination. With unlimited resources of course all tactical approaches can be used simultaneously, but in real life situations one of the IC’s main tasks is to prioritize the possible missions with respect to available resources.

FULL SCALE TESTS IN THE BRUNSBERG TUNNEL
The full scale fire and explosion tests within the METRO project were performed in the abandoned Brunsberg rail tunnel during September 2011. In total four tests, with each one week interval, were performed, see table 1. For the tests X1 commuter trains placed at the METRO project’s disposal by the Stockholm Public Transport were used. The first test performed was an ignition test underneath a not rebuilt X1 train, which also was used for the second full scale tests the week after. The third test was performed in an X1 train that had been rebuilt to correspond to a newer C20 metro train regarding surface, isolation and seats. The length of an X1 carriage is 24 meter, while two connected carriages is in total 49.95 meter. The two full scale fires were initiated by a small amount of petrol, imitating an arson attack. Left luggage was placed at 81% of the seats, with a mean weight of 4.44 kg. No consideration was taken to left luggage from standing passengers. The number and weights was based on an earlier field study performed in the Stockholm Metro [17].The fourth and last test was an explosion tests, performed with a hand carried-sized charge placed at a seat. In this test two similar original X1 trains were connected and placed together inside the tunnel. The aim was to investigate the effect on the two trains, measure the pressure distribution, investigate the possibilities to perform a rescue operation and estimate the possible injuries at the passengers at different locations. The fire test was performed in cooperation between SP, Mälardalen University and Greater Stockholm Fire Brigade. The final explosion test was lead by FOI – the Swedish Defense Research Agency in collaboration with the three organizations mentioned above.

The old Brunsberg tunnel is 276 meters long and located next to an active track. The test area was closed and supervised during all tests and all traffic and activities at the nearby active track was totally suspended during the time for the explosion. The tunnel has a mean height of 6.9 m and a mean width of 6.4 meter at ground level. The surface roughness of the tunnel varies between 0.2 and 0.3 meter. A MGV L125 trailer mounted PPV ventilator, with the capacity of 217,000 m$^3$/h (eq. to 60.3 m$^3$/s), was placed at the east end of the tunnel in order to direct the smoke to make temperature and HRR measurements possible. The mean air velocity before ignition varied between 2.0 and 2.5 m/s. The PPV ventilator also made it possible for the fire and rescue services at all to be located, up-streams, close to the fire. The tunnel has a slight inclination from the west to east and the front of the train was placed 84 m from the east adit. The distance between the train side and the tunnel was 1.3 m on the left hand side and 1.9 m on the right hand side, seen from upstream side of the train.
The water supply was covered by two water pumps placed at the nearby lake at a distance of 115 meters from the eastern adit. The main pump was of type III (2400 l/min. at 10 bar) and a type II (1200 l/min. at 10 bar) as back up. The supply hoses had a diameter of 63 mm and the operating hoses 42 mm, with traditional fog-fighter nozzles with an approximate maximum flow of 300 l/min. The BA-rescue front team was equipped with one IR image camera and a helmet mounted video camera. In addition to the two BA-rescue teams a fire robot, also equipped with an ordinary video camera and an IR image camera was tested. The main aim of using the fire robot was to test the operation of the robot itself and to make images from downstream the tunnel facing upwards, from a position where the BA-rescue teams for safety reasons not could be located.

The five fire fighters who participated in the full-scale tests were between 25 and 45 years old. All have extensive experience in emergency services in general and BA-operations in particular. Two of the five fire fighters are instructors for BA-operations and two of them have requisite training for BA-rescue command. Water supply and operation of the mobile fan was covered by additional personnel. Each test was documented by observers, placed outside the tunnel adit for visual observation and inside a fully equipped command vehicle, for overhearing the BA-rescue radio channels. The BA-rescue teams were running reporting air consumption, location and observation to the command vehicle and the fire fighters were equipped with pulsimeters. The locations and experiences were later compared to the actual recorded measurements in the tunnel, for example regarding temperature or heat radiation. During the fire tests the tunnel was equipped with 102 thermocouples, 9 plate thermometers for heat radiation measurements, 18 gas analyzers, 6 bi-directional probes for air velocity measurements and 4 laser detectors measuring the visibility inside the train. In addition to the measuring equipment cameras was placed both inside the train and in the tunnel - on the side of the train and up-stream the fire.

At the first fire ignition test the planned set up of the BA-operation was tested. The BA-rescue teams were also assigned to extinguish the fire in case of fire spread underneath the train, as the same train should be used in the second test. Only minor changes was made in the fire and rescue set up for the two following full scale fire tests. For safety reasons a full BA-rescue organization was set up, consisting of one BA-rescue team at the front as close as possible to the train, one BA safety team 75 meter behind, a BA-rescue commander outside the tunnel and an IC responsible for general decisions. A BA-team consists of two BA fire fighters. During the final explosion test a closed safety zone comprising the tunnel and 50 meter from each tunnel adit was decided for safety reasons. FOI – main responsible for the explosion tests – searched the train and the tunnel prior the test and kept guard outside the safety zone until the explosives had detonated. No fire followed the explosion. FOI personnel together with the fire and rescue services entered and secured the tunnel in order to make non-disturbed observations before the project photographers and the rest of the observers were allowed into the tunnel. The fire and rescue service’s experiences entering the scene of the explosion was filmed by a helmet-mounted camera for later analyzes.

**RESULTS AND OBSERVATIONS**

The temperatures and HRRs measured in the tunnel are presented in detail in other publications [18] and are here only presented as maximum values. The first ignition test did not affect the ceiling
temperature at all and no fire spread could be seen outside the area directly heated by the flames.

<table>
<thead>
<tr>
<th>Test</th>
<th>Type</th>
<th>Max HRR [MW]</th>
<th>Max temp. (above train) [˚C]</th>
<th>Max temp. (downstream) [˚C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ignition</td>
<td>0.5*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Fire</td>
<td>76.7</td>
<td>1073</td>
<td>1081</td>
</tr>
<tr>
<td>3</td>
<td>Fire</td>
<td>77.4</td>
<td>1118</td>
<td>980</td>
</tr>
<tr>
<td>4</td>
<td>Explosion</td>
<td>No fire</td>
<td>No fire</td>
<td>No fire</td>
</tr>
</tbody>
</table>

Table 1 Temperatures and heat release rates [18]

*HRR for actual heptanes pan measured in laboratory environment. [18]

The HRRs and the temperatures in test 2 and test 3 are similar and the biggest difference between the two tests was the time until a fully developed fire inside the train. For short description of tests, see table 1. Test 2 corresponded well to the earlier performed laboratory tests performed at the SP fire lab during the summer 2011 [19] and a fire with temperatures above 600˚C could be seen after approximately 3 minutes. The maximum HRR was measured after approximately 13 minutes. In test 3, with the rebuilt carriage with mainly incombustible surfaces and partitions that effectively prevented heat radiation between the main compartments the corresponding times were measured to 108 minutes for temperatures above 600˚C respectively 118 minutes for maximum HRR. The fire behavior, apart from the initial time to reach a fully developed fire, though has many similarities in maximum values and duration. Both fires declined to the size of a larger car fire in approximately an hour [18, 20]. The results clearly show that incombustible surfaces gives the passengers valuable extra time to evacuate as well as the fire and rescue services time to reach the fire while it is at a size possible to extinguish. With the resources available at a normal sized Swedish city fire and rescue service, i.e. a minimum of ten fire fighters in the second line of response, the fire represented in test 3 would have been extinguished successfully. At favorable circumstances (short response route, easy access) the fire could have been extinguished by the first line of response with fewer personnel after regular risk estimations.

Due to the air flow created by the mobile ventilator in order to direct the smoke in one direction the influence on the visibility at the location of the front BA-team a was limited. The BA-teams had a unique opportunity to study the fire development at a large train fire from a distance that at a real accident not would be possible to be located at, due to heat radiation from the fire and re-radiation from the smoke layer. Without ventilation, further away from the fire, the full tunnel cross-section instead would be filled with smoke [21]. The smoke would effectively prevent the BA-teams from seeing the fire through plain sight and the visualization would instead be reduced to the use of an IR-imaging camera.

In spite of the mobile ventilator some back-layering could be seen both in test 2 and test 3. The working environment, at ground level, was in all three fire tests close to normal conditions with no significant exposure of high temperature or heat radiation affecting the fire fighters. In test 2 the back-
layering under a short duration, at approximately 6 minutes from ignition, advanced fast to 50 meter upstream the fire and stretched to the eastern tunnel adit before the effect of the mobile ventilator was adjusted to direct the smoke in the east to west direction. During the fast progression of the back-layering the BA-teams retreated from their advanced position for safety reasons, but re-established the position after less than three minutes. In both test 2 and test 3 strong pulsations could be seen in the tunnel. These phenomena was first discovered in the Runehamar tests in 2003. The pulsations depend on the HRR, the effect of the ventilation (natural or mechanical) and the properties and length of the tunnel [22]. Outside the tunnel adit observations were made of light objects moving back and forward over a distance of approximately 20 meter. During the strongest pulsations brushwood outside the tunnel swung almost to the point that frail branches broke and loose equipment, paper and rubbish were thrown around. The pulsations affected the mobile ventilator and the ventilation motor’s changing number of revolutions, due to the changing counteracting resistance in the tunnel, could clearly be heard at the eastern adit.

In test 1 and 2 a ROV with mounted conventional and IR-imaging cameras was used to picture images downstream the fire. The ROV was also used to provide the project with images from angles where projections in high and low sensitive mode could be recorded for later evaluation. From the position downstream the fire, the burning train carriage as well as the BA-rescue teams upstream the fire, could be viewed in the camera. The filmed sequence shows that the sensitivity of the camera automatically switches to “low” when the flames from the fire appear in the viewfinder. The appearances of the BA-rescue team then was largely reduced. This perfectly normal function in the camera could obscure a potential victim if a BA-fire fighter is unaware of the camera’s limitations. This shows that the pictures from the IR-image camera can be difficult to comprehend for the BA-rescue team and that the use of the IR-image camera can be reduced in situations where the search needs to be performed from a distance and the fire blocks the way. Earlier performed tests also showed that the tunnel environment further away from the fire, when the smoke temperature has declined and the smoke fills the entire tunnel cross-section [21, 23], shows very low thermal contrasts. Low thermal contrast will make it difficult for the BA-rescue team to evaluate the images from the IR-image camera and estimate borders and directions [23].

![Figure 5: Beside train pointing upstream fire, high sensitivity mode.](image1)

![Figure 6: Beside train pointing upstream fire, low sensitivity mode.](image2)

![Figure 7: Beside train pointing upstream fire, low sensitivity mode, info ThermColouring](image3)

![Figure 8: Beside train pointing upstream fire, low sensitivity mode, info ThermColouring](image4)
The communication between the remote control and the ROV worked well and pre-tests prior to test 1 showed no interference between the ROV radio communication and the measuring equipment. The low center of gravity turned out to make the ROV stable and it had no problems to cross water hoses or move next to the track on gravel and macadam. These tests results, regarding maneuver and control of the ROV, should be seen as preliminary and more extensive tests need to be carried out.

The mobile PPV ventilator used in the tests did well power to redirect the smoke in the desired direction. The ventilator was used in the range of 60-75% of its full capacity. The ventilator was affected by the pulsations and the back-layering and, in short duration, got over-powered before the right air flow could be set. The situation clearly showed that the ventilator more easily can withhold a flow if a counteracting pressure already has been established than to redirect a flow moving towards the ventilator. Pre-tests showed that the ventilator is more effective inside the tunnel or at the tunnel adit, than outside the tunnel with the air cone covering the tunnel opening [24]. The sound-level in the ventilator vicinity would though easily cause communication problems especially between the BA-rescue commander and the BA-rescue teams.

After test 4 – the explosion test – the first BA-team entered the east tunnel adit approximately two minutes after the detonation. The train was thereafter reached in an additional minute. The short response time in this test does not correspond to the conditions applicable at a real rescue operation after an explosion. In test 4 there was initially no forced mechanical air flow and the natural wind velocity in the tunnel was negligible. There was only a slight haze of smoke inside the tunnel, mainly due to dust, and no fire was observed. The IR-image camera showed a very low heat signature close to the former location of the explosive device. Major damage was observed on the first train carriage and slight damage to the connected rear carriage. The front carriage had de-railed and the roof had split open to both sides. The deformation obstructed the tunnel and made it difficult for the fire fighters to reach the second carriage. Tactical extrication can be complex in open air and the tunnel environment represents additional challenges for the fire and rescue services. In a real life situation it would have been very difficult and time consuming to transport cutting and heavy rescue equipment or injured passengers on stretchers past the obstructed parts in the tunnel.
The blast effectively put out all camera and lightning equipment in the carriages and a real rescue situation would require setting up of primarily lightning in order to effectively rescue passengers. The direct effect on the passengers could be divided into four types;

1. Over pressure (from shock wave)
2. Fragmentation (shrapnel and scattered pieces of primarily train interiors)
3. Impact (passengers thrown towards rigid surfaces)
4. Heat (from thermal wave)

Thermal wave effects can be considered relatively limited in non-military situations. The main types of injuries for the first responders to deal with in an underground train explosion would be passengers affected by shock wave or fragmentation. The human body can resist relatively high shock waves but are, for natural reasons, vulnerable to fragmentation. In cases where the rescue is delayed the risk of fatality due to lethal bleeding increases [25]. The pressure distributed to the second carriage was in a range which would be possible to survive. The second carriage would most likely represent a location where passengers with less effort and resources could be rescued [26]. Adjacent carriages, not blocked by the demolished carriage of origin, would also be easier to reach for the first responders and increase the possibilities for survival. An observation of importance is though that the over pressure in the tunnel, outside the carriages, caused a blocking of the doors in the second carriage, which would cause problems evacuating especially if the explosion is followed by a fire.

Under real circumstances, it is likely to take anything between ten minutes and one hour before the first BA-rescue team arrives at the scene of the fire in a train tunnel. The front transportation speed for a fire and rescue operation and full water hose lay-out, with respect to the Swedish Working Environment regulations [27], are between 0.1 and 0.2 m/s [24]. The maximum distance a fire and rescue operation can cover with consideration to the safety regulations mentioned above and air supply of compressed air is approximately 200-250 meters. To cover longer distances the BA-rescue teams need to move partly or fully without water supply, use longer lasting air supply for example oxygen systems and use transportation trolleys or vehicles. Oxygen systems for BA-rescue operation though cause other challenges to consider. In the tests the fire fighters physical condition was monitored regarding for example pulse and air consumption. The outcomes of the measurements is not discussed further as the tests, in respect to correspondence to real life conditions regarding strain, heat exposure and stress levels, not are applicable.

CONCLUSIONS
After the tests all involved fire fighters and engineers were interviewed and the results from the measurements, observations and interviews are summarized below;

1. The different surfaces of the train interior created totally different conditions and possibilities for both evacuation and fire and rescue operations.
2. For the conditions in test 2, with non rebuilt train interior and fast fire development, the fire and rescue services would most likely not be able to reach the train in time in order to extinguish the fire.
3. For the conditions in tests 3, with rebuilt train interior and slow fire development, the fire and rescue services would relatively easy be able to stop the fire developing to flash-over.

4. Even if an under ventilated fire inside the train could occur the fire environment in the tunnel itself could be considered well ventilated, with or without mechanical ventilation. In respect to this the requirement of safe water supply at all times should be discussed in national Swedish fire fighting. The common apprehension is not to move inside the tunnel without a filled water hose. This prevent the possibilities to send BA scout teams or BA-rescue teams that move without water and connect to mounted water hydrants inside the tunnel when the conditions require water supply.

5. The mobile high flow ventilator created a very favorable environment upstream the fire. The risk for increasing the HRR must though be taken into consideration as well as the conditions for evacuating passengers in case of re-direction of the flow inside the tunnel. The best location for mobile ventilation is at the tunnel adit or inside the tunnel.

6. The sound-level from the mobile ventilator could cause communication or working environment problems at the tunnel adit.

7. The use of IR-imaging in tunnels, both close to and further away from the fire, needs to be further evaluated. Education material and images would be of use for training of BA-rescue in tunnels.

8. Robots or ROVs for scouting and search beyond the fire scene are very useful and should be further developed.

9. There is need of development and evaluation of different types of search patterns for tunnels. Normal IR-image search methods used in compartment fires are not applicable.

10. The over pressure in the tunnel can make doors at adjacent carriages to stuck in closed position (test 4).

11. An explosion inside a train carriage in a tunnel can cause blocking effects that influences the fire and rescue operation.

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REFERENCES
1. www.metroproject.se
4. Bergqvist, Anders, “Internal report from the Kaprun fire in Austria” (in Swedish), Stockholm Fire Department, 2001
11. “Memorial Tunnel Fire Ventilation Test Program,” Massachusetts Highway Department, Federal Highway Administration, CD-rom, Parsons Brinckenhoff 4D Imaging, 1996