THE METRO PROJECT

Final report

Ingason, H., Kumm, M., Nilsson, D., Lönnermark, A., Claesson, A., Li, Y. Z., Fridolf, K., Åkerstedt, R., Nyman, H., Dittmer, T., Forsén, R., Janzon, B., Meyer, G., Bryntse, A., Carlberg, T., Newlove-Eriksson. L., Palm, A.

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Photo: Per Rohlén

STUDIES IN SUSTAINABLE TECHNOLOGY

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Preface

The idea to the METRO project started after the seminar *Safety in Infrastructure* in Budapest 2004. In the beginning it was meant to be a bilateral Swedish-Hungarian cooperation. Unfortunately, this was not possible due to financial reasons. Therefore it developed to a fully Swedish funded and performed research project. There was, however, continous cooperation and discussions with the Budapest Fire Department which was of great importance for the project. It has been an interesting journey from Budapest 2004 to the Brunsberg tunnel in Arvika 2011 – the location for the full-scale tests - to the final seminar at the old rescue school at Rosersberg outside Stockholm in December 2012.

Before the start none of the participants could imagine how much attention the project would get worldwide. We are all thankful that we have been a part of this successful project and hope that we have contributed to move the research front line a few steps forward.

Without the support from different fire brigades, researchers, students, authorities and finaciers in Sweden, this journey could never end as well as it did. We feel that we have contributed to safer metro systems. It is vital as metro systems become more and more complicated and there is still a need for further research acitivities. The fire safety and security issues will continue to be important even in the future.

This report summarises the work that has been carried out in the project during these three years of research. There are references to all the detailed reports produced and many of them are available online. There are, however, few security research reports that had to be classified due to the content of the reports. Access to restricted reports can be allowed on request and after regular security procedures. Hopefully this summary reports gives you guidance in finding the information needed for further research or investigations in your field of research or engineering design applications.

Sweden, December 2012
Ingason H., Kumm M., Nilsson D., Lönnermark A., Claesson A., Li Y.Z., Fridolf K., Åkerstedt R., Nyman H., Dittmer T., Forsén R., Janzon B., Meyer G., Bryntse A., Carlberg T., Newlove-Eriksson L., Palm A.

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Abstract

The report compiles the results from the METRO-project. The different parts of the project; design fires, evacuation, integrated fire control, smoke control, extraordinary strain on constructions and fire- and rescue operations are presented separately.

The most complicated and expensive part of the project was the performance of the large scale fire and explosion tests in the Brunsberg tunnel. The maximum heat release rates measured from the metro carriage was 77 MW. The maximum ceiling gas temperatures was 1118 °C. These values are high, and should be put into a perspective of the situation and the type of carriages used. The project is not recommending the highest values as the design fire, but values reflected in conditions.

The egress study confirm that one of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate an evacuation. New data show that participants moved with an average of 0.9 meters per second in the smoke filled environment (average visibility of 1.5–3.5 meters). A way-finding installation at the emergency exit, which consisted of a loudspeaker, was found to perform particularly well in terms of attracting people to the door.

Two smoke control systems were simulated for a single exit metro station. The systems consisted of a pressurizing supply air system and mechanical exhaust ventilation system with and without platform screen doors. The results show that both the pressurizing supply air system and the mechanical exhaust air system provide effective smoke control for one exit metro station. The significance of the platform screen doors was shown to be important in relation to smoke control.

Experiments and simulations have provided increased confidence in ability to simulate explosion scenarios to determine the pressure inside and outside a carriage and to be able to study variations of conditions such as carriage geometry and window designs. The explosion test performed show that an explosion with a relatively minor charge can significantly change the conditions for both evacuees and the rescue service. The results show that the conditions for evacuation and rescue operations can change dramatically as a result of a relatively minor explosion. Evaluation of methods and fire and rescue tactics in metros is given. Mapping of IR imaging as a tactical resource at tunnel fires was presented.

1   Introduction

Underground metro rail systems are complex infrastructures of considerable importance for their communities and users. They create a situation in which many users share a relatively limited area at the same time. This creates considerable risks, with the tunnel fires that have occurred in recent years showing clearly that a fire can have both major and deadly consequences. The mass transport system must be constructed so that people sense that they are safe and secure when travelling. A lack of confidence in the system is devastating for both society and mass transport companies. Knowledge of the consequences of a fire incident or a terrorist attack in a metro system is therefore of utmost importance.

There is a great need to improve the knowledge in many different fields of fire safety and security in metro systems. In large cities, in order to make better use of valuable land for building or recreation purposes, metro systems are a common and effective solution. Many metro systems have parts built many years ago and a few are not yet opened. They thought have in common the parameters many passengers at a limited area underground, long escape routes and complex fire and rescue operations in case of fire.

In the last 40 years a number of serious fire accidents have occurred in metro systems around the world. A total of 289 people were killed and 265 severely injured in an accidental fire in the subway of Baku, the capitol of Azerbaijan, 28th of October 1995 (Rohlén and Wahlström, 1996). Similarly, some 198 people were killed and 146 injured in the Daegu subway arson attack of February 18, 2003 (Burns and Gillard, 2003). Two of these fires have caught the focus of this project, namely the effects of the luggage on the fire development. The fires in the Bakus metro in 1995, and the Kaprun mountain railway tunnel in 2000, show that abandoned clothing and baggage can play an important part in the progress of the fire.

Risks for terror attacks have been existing for a long time. Moreover, and particularly since the 1990s, experiences from among others, the IRA Underground attacks in London, the 1995 Sarin gas attack in the Tokyo subway, the 2004 commuter train attacks in Madrid, numerous attacks on the Moscow subway, and the 2005 London bombings have led to an increasing appreciation for the risks of hostile attack on urban rail infrastructure (Beaton et al, 2005; Taylor et al, 2005). 'Traditional' structural risks in rail transport infrastructure projects and fire and smoke risks have thus increasingly been augmented by newer risks of terrorist attacks on passenger trains and stations. Indeed, historical analysis of terrorist incidents over the last 80 years indicates that public transportation and specifically subways and trains have

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become increasingly favoured targets (Taylor et al, 2005). In addition to conventional risks and terrorist threats posed to the subways and tunnels in urban centres, there are problems posed by increasing traffic volumes and ensuing pressure on infrastructures. The trend towards multiple structures of ownership and the multiplicity of actors working in particularly high-traffic urban stations and on trains, poses further challenges, for example, in information management and communication.

The METRO project focus on fire and explosion as two separate events, but a combination of these two hazards can potentially lead to even worse consequences. The reason for this separation is that a fire after an explosion destroys the possibility to post-observation of the explosion consequences.

The knowledge about fire development in metro carriages is limited. This is one of the main reasons for performing the full scale fire tests as part of the METRO project. Authorities and engineers working on safety and security aim to provide users with a high level of confidence in public systems, but safety and security come only at significant cost and it is often necessary to compromise between cost and benefits. Installing a water spray systems in the entire metro system to prevent the development of a fire is not possible and unrealistic from a cost-benefit point of view.

A central part of the METRO project was the large-scale fire tests with commuter train carriages in a tunnel. The main aim of the large-scale test was to illustrate in a mass transport system the limitations, consequences and risks when such a carriage starts to burn, or is subject to a terrorist attack. Such large-scale tests gives information on fire spread and development, the limits for flashover, radiation towards people, structures and equipment, conditions and possibilities for the rescue service personnel, and much more. The large amount of resources needed (personnel, material, equipment, transportation, etc.) to perform large-scale fire tests with carriages means that the number of full-scale tests that were performed is limited. Still such full-scale tests are very important both for understanding of the fire behaviour and for comparison with computer simulations and model-scale tests. One example of a test performed with a metro car is from the extensive EUREKA 499 test series (see recent summary from these tests in Ingason and Lönnermark 2012). In that test series, a German metro car was used giving a maximum HRR of 35 MW. In the same test series, tests were performed with different types of railway cars with maximum HRR between 13 MW and 43 MW. Given the range of HRR and the diversity of railway carriages and tunnel dimensions, there is clearly a need for further large-scale data.

Egress situations at metro stations are usually complicated for the users and the owners. The rescue teams may have difficulties in organizing the rescue operations due to the complexity of such egress situation. It is mainly due to the large number of persons, differences in levels, long escape routes, etc., which all complicate evacuation and rescue efforts. The speed at which a fire develops, and the resulting conditions inside carriages and in the tunnel, is decisive in determining whether passengers can escape safely.

This unique project has been running for the last three years, from 2009 to 2012. The results have received enormous publicity and in this final report, the individual tasks and results from the different work packages are summarised. The conclusions and recommendations given in chapters 11 and 12, respectively, contemplate the essence of the project. It is the au-

thor's hope that this report may enlighten and be of use for future research projects and engineering challenges in large infrastructure projects.

2   Background

The METRO project is a Swedish research project about infrastructure protection in mass-transport underground rail and metro systems. The focus was on tunnels and subway/metro stations, and both fire and explosion hazards were studied. It is a multidisciplinary project where researchers and PhD students from nine different disciplines cooperate with practitioners with the common goal to make underground rail mass transport systems safer in the future. The METRO project (www.metroproject.se) was a three year undertaking, running from December 2009 to the December of 2012. The main objective of METRO was to create a safer environment for passengers, personnel and first responders in the event of fire or terror attack in underground mass transport systems.

The following nine partners participate in the METRO project: Mälardalen University, SP Technical Research Institute of Sweden, Lund University, Swedish Defense Research Agency (FOI), Gävle University, Swedish National Defense College, Swedish Fortifications Agency, Greater Stockholm Fire Brigade and Stockholm Public Transport (SL). The total budget of METRO was 19 million SEK. METRO is funded by the following six organizations: Stockholm Public Transport (SL), Swedish Civil Contingencies Agency (MSB), the Swedish Research Council Formas, the Swedish Transport Administration (Trafikverket), the Swedish Fortifications Agency (Fortifikationsverket), and the Swedish Fire Research Board (Brandforsk).

The work in METRO was divided into seven work packages (WPs) which address different aspects of the studied topic:

- WP1 – Design Fires
- WP2 – Evacuation
- WP3 – Integrated Fire Control
- WP4 – Smoke Control
- WP5 – Extraordinary Strain on Constructions
- WP6 – Fire and Rescue Operations
- WP7 – Project Management (not discussed further in the report)

WP 1 – Design fires - is the largest work package, and consequently requesting the largest resources. It involved model scale tests (at the scale of 1:3), laboratory tests and full-scale tests in a real railway tunnel (the Brunsbergtunnel). The aim of WP1 is to gain basic data re-

garding for example heat release rates, temperatures, optical density and combustion products as well as reliable correlation models between model and full-scale tests. One of the most interesting areas to investigate is how the ventilation conditions, i.e. the openings consisting of doors and windows, influence the fire development. The early stages of the fire development are of interest when designing evacuation strategies for trains or stations, while the fire behavior for the fully developed fire are needed for areas involving construction safety or rescue operations. The model scale tests are intended to, together with the full-scale tests, to become a solid base for later validation of existing computer models. The tests also increase the knowledge of fire performance of train interiors.

These large scale tests are, in fact, unique in several ways: partly in terms of their performance, bringing together many research and working disciplines actively to participate in the tests and benefit from the results, and partly because typical luggage is used in order to provide an additional fire load in the tests. Earlier tests have been carried out without considering the luggage carried by passengers, and possibly left behind when the train is ed. For this reason, as part of the work of the METRO project, a field survey was carried out on Stockholm commuter trains and underground trains, under the leadership of the Mälardalen University in conjunction with SL and MTR (the operator) in Stockholm. The survey looked at what, and how much, luggage the passengers had with them. Tests were carried out in SP's fire laboratory, burning typical bags in order to determine their heat release rates and energy contents. The fact that passengers' luggage can increase the risk of spread of fire in a metro carriage is one of the most important tasks within WP1.

The **WP2** – Evacuation – gives information about how to design safe evacuation from trains, tunnels and stations for all groups of society, with special consideration taken to persons with disabilities and senior citizens. Medium scale evacuation tests performed in cooperation between Lund University and the Stockholm Public Transport – SL provides makeup dates of existing evacuation simulation software possible, regarding evacuation from trains in tunnels and at platforms.

The **WP3** - Integrated Fire Control - is coordinated by SL and investigates state-of-the-art techniques for fire safety in underground mass-transport systems. One of the goals is to evaluate the interaction between technical and organizational measures.

The **WP4** - Smoke Control - concentrates on smoke control by using jet-fans in single-exit stations. In these stations, the smoke, the evacuating passengers and the first responders all have to share the existing path between the platform and the ground-level. By using jet-fans to control the smoke, the evacuation routes, as well as the first responders' response route, can be kept free and facilitate the evacuation and the fire and rescue operation. Special focus is directed towards air and smoke movement, temperature distribution and smoke-layer analysis.

The **WP5** - Extraordinary Strain on Constructions - produces reliable results that can be used for designing safer underground facilities and to estimate the design explosion which the constructions should be able to withstand. To protect all passengers at all times will be an impossible task, but sustainable and reliable constructions will increase the protection level for the passengers and make the working environment for the first responders safer. Both model and full-scale explosion tests are performed and the strength of different constructions

after they had been exposed to fire or explosion is estimated in order to secure the working environment for the first responders. Strain and stress on relevant parts of the constructions is modeled and vulnerable components of the structures identified. Solutions for minimizing consequences in case of extraordinary events is proposed and the knowledge helpful for end-users, first responders and designers of the infrastructure.

The **WP6** - Fire and Rescue Operations - focuses on the fire and rescue operations in tunnels. This is in general a difficult and complex task. In underground mass-transport systems, not only long response routes, but also the amount of people that might need assistance to evacuate, can cause problems for the fire and rescue organizations. The maximum possible response range for the fire and rescue services, in worst cases, can be as short as a hundred meters if the transportation has to be performed in dense smoke. In these cases it will also take a considerable amount of time to cover the distance. Evacuation from underground tunnels and systems must be based on self-evacuation, but this is not the case at all places in many already built transportation systems. A new tactical approach for the fire and rescue organizations is one of main tasks of WP6.

Close cooperation between all work packages provides designers, owners, authorities and the first responder community with valuable information about the limits, and possibilities, for fire safety engineering design and fire and rescue operations in metro systems. As often the conditions for fire and rescue operations in underground mass-transport systems are difficult the knowledge about how innovative measures, equipment and material can be used as a tactic resource in the case of fire constitutes a crucial area.

Based on the results from the tests and analyses, design tools and field-guides were developed. This will support the fire and rescue organization both in their preventive work as well as in facility design, the contingency planning and the operational firefighting.

3   WP1 – Design Fires

In order to design the fire safety measures in metro systems, a design fire is an important parameter. When performing risk analyses, egress planning or modelling, construction calculations, etc., different fire scenarios or design fires are selected. To be able to model the fire scenarios, curves are needed to describe the fire development. For this often heat release rate (HRR) curves are used. The knowledge about heat release rate forms the basis for the development of the design fire curves. The correlations between different scales are also of significant importance since it will indicate the relevance of the results in different scales.

A good starting point is the survey carried out by Ingason and Lönnermark (2012) who made a summary of the heat release rate tests carried out, see Table 1. The tests on the coach car and a subway car, which were presented recently by Hadjisophocleous et al. (2012), are missing in the original survey. The majority of the tests available are from the EUREKA 499 test series (EUREKA 499, 1995).

Hadjisophocleous et al. (2012), presented heat release rate measurements from a test using an intercity railcar (coach car) and a test using a subway car. They concluded that the heat release rate for the two cars measured show clearly that fire development and maximum heat release rate is governed by the ventilation conditions that exist during the fire. The intercity car which had a much higher fire load density reached a lower maximum heat release rate than that of the subway car. The duration, however of the subway fire was much less than that of the coach fire due again to the lower fire load density. These tests were not available to the project at the time the large scale fire tests were performed.

The test results presented in Table 1 are based on tests with single coaches. The peak-HRR is found to be in the range of 7 to 53 MW and the time to reach the peak HRR varies from 5 to 80 minutes. In all cases, except the German subway car, the fire growth rate was about **medium** fire growth rate following the t-square (t^2) fire growth rate according to the definition in NFPA 72E. The German subway car was following the **ultra-fast** fire growth rate curve.

Table 1   Large scale experimental data on rolling stock

Type of vehicle, test series, test nr, u=longitudinal ventilation m/s	Calorific content (GJ)	Peak HRR (MW)	Time to peak HRR (min)
A Joined Railway car; two half cars, one of aluminum and one of steel, EUREKA 499, test 11, u=6-8/3-4 m/s	55	43	53
German Intercity-Express railway car (ICE), EUREKA 499, test 12, u=0.5 m/s	63	19	80
German Intercity passenger railway car (IC), EUREKA 499, test 13, u=0.5 m/s	77	13	25
British Rail 415, passenger railway car*)	NA	16	NA
British Rail Sprinter, passenger railway car, fire retardant upholstered seating's*)	NA	7	NA
German subway car, EUREKA 499, u=0.5 m/s	41	35	5
Coach car, (Hadjisophocleous et al. 2012)	50	32	18
Subway car, (Hadjisophocleous et al. 2012)	23	53	9

*) The test report is confidential and no information is available on test set-up, test procedure, measurement techniques, ventilation, etc.

A complementary information was needed on fire development in metro carriages and therefore it was decided to do further large scale testing using metro carriages. During the autumn of 2011, after the model scale tests and the laboratory ignition tests were performed (see Lönnermark et al 2011 and Claeson et al 2012), full-scale tests in an abandoned railway tunnel in central Sweden were performed. The project had access to three metro carriages, where two were used for fire tests, and one for explosion test. Before the results from the large scale tests are presented, a summary of the model scale tests and the laboratory tests are discussed.

Model scale fire tests (1:3)

A total of 10 tests were carried out to investigate the effect of fuel load, openings and ignition location on the fire development in a metro carriage (1:3). The fuel loads consisted of PUR seats, wall and ceiling linings, floor coverings, and in some tests longitudinal wood cribs simulating the luggage and other combustible materials. Different parameters including: heat release rate, gas temperature, gas concentration, heat flux and smoke density, were measured in the tests.

The fuel load plays a very important role in the fire development in the tested metro carriage. In the tests, the most important part of fuel loads for fire spread was the longitudinal wood cribs, see Figure 1. The fire did not spread from the seats when these were the first point of ignition without the longitudinal wood cribs and, therefore, the heat release rate remained in those cases at a very low level for an extended period in these tests. To obtain a high heat release rate this part of fuel load is necessary in the metro carriage. Another important part of the overall fuel loads includes the walls and ceiling coverings which support rapid growth of the fire. It can be concluded that to obtain a high heat release rate or to get the metro carriage fire more fully developed, there must be enough fuel available and distributed in such a way in the metro carriage that the initial fire can spread to seats beyond the initial point of ignition. The long wood cribs were important for the fire to spread and involve

the entire metro carriage. On the other hand, the wall and ceiling linings were important for the speed of the fire spread.

Figure 1   A photo of the model scale experiments (1:3). The door to the left is door DR1 and the one in the middle is door DR2.

Another important parameter was the ventilation. In theory, the fires were fuel controlled, i.e. when the maximum measured heat release rate is compared to the theoretically possible flow of oxygen through the opening; but the distribution of the fuel load in relation to the openings proved to be important. In some cases, the conditions became locally under ventilated and during periods of these tests, the flames were located mainly near the doors (or other openings). Therefore, the maximum heat release rate may still be dependent on the number and positions of the openings. In tests without fire spread, due to restricted fuel load, the vent opening had no influence on the fire development. In tests with larger openings and fire spread, the fire grew more rapidly. The maximum heat release rate was found to increase with the area of the openings since more rapid fire development resulted in more fuels burning simultaneously. The air flow inside the metro carriage model might also have been altered by the number and positions of the openings. It was observed that the fire spread met an opposing air flow to the left of the first door (DR1), while aided by the airflow when past door DR1.

The location of the ignition source had limited influence on the fire development. The results show that placing the ignition source between door DR1 and the second door DR2 (one in the middle in Figure 1) increased the fire growth rate, although it was not found to affect the maximum heat release rate significantly. The maximum heat release rate in the test with ignition between the doors was actually somewhat lower than other equivalent tests.

It was observed that the local flashover occurred in the section close to DR1 first, and then move to the other side until finally the entire carriage was involved in the combustion in some tests when fire spread occurred. The reason for this behavior was that a carriage is very long, similar to a tunnel. The temperature decreases along the distance away from the fire source, thus the parts distant from the initial fire need much more time to reach local flashover. Here the local flashover is defined as the state that the fire in this zone is fully developed,

characteristic as a floor temperature of 600 °C or a floor oxygen concentration of about 0 %. The results of local flashover time suggest that the rate of fire spread from one corner to another is approximately constant. In the last test with six doors open, the spread from left corner to right corner takes about 10 min, corresponding to 17 min in full scale. The heat release rate in such cases could be as high as about 1243 kW, corresponding to about 20 MW in full scale. For further information please read the full technical report and see the availability in Appendix:

- Lönnermark, A., Lindström, J. and Li, Y.Z. (2011). Model-scale metro car fire tests, SP Report 2011:33, Borås, Sweden.

- Lönnermark, A., Lindström, J., and Li, Y. Z. (2012). "Model Scale Metro Carriage Fire Tests - Influence of Material and Fire Load", Second International Conference on Fires in Vehicles, pp 159-169, Chicago, USA, 27-28 September.

Laboratory tests with 1/3 of a train carriage mock-up

Instead of conducting numerous ignition tests inside a full scale carriage, it was decided to conduct some preliminary ignition tests in a laboratory environment, where it was easy to measure the heat release rate. This was a more efficient way to compare numerous ignition scenarios, rather than to do tests that may risk developing into a full flashover inside a tunnel. The purpose was twofold, firstly to understand the impact of the ignition source on the possibility to develop to a fully flashover type of fire, and to understand what parameters in the process that are dominating or governing the process from ignition to flashover. Secondly to obtain the basic information needed for each material used in the full-scale and laboratory scale presented in this report.

A total of six tests were carried out in the 1/3 train carriage mock-up. The amount of fire load (luggage and wood cribs) was increased during the test series. The heat release rate from the ignition source was also increased and in the last two tests the ignition source was changed from solid to liquid.

Even though not all tests reached a fully developed stage, the fire spread approximately followed the same pattern in all tests. First the fire spread from the ignition source towards the opposite seat, then across the midsection of the carriage, still limited to the rear section of the carriage, see Figure 2. Finally, the fire spread towards the opening, forward in the carriage, across the full width of the carriage. When and where the fire stopped or whether it reached a fully developed stage was mostly dependent on the amount of fire load and how strong the vertical flame spread on the High Pressure Laminate (HPL) boards mounted to walls and ceiling above the ignition source was.

Figure 2 **Photo taken shortly after the fire starts to spread from the initial fire source with poured petrol in the right corner combined with combustible material on the walls, seats and luggage.**

In the first three tests the fire never reached a fully developed stage and the decay started before the fire spread from the origin fire zone. In the fourth test on the other hand a flashover was observed. The difference between these tests was the additional luggage placed in the ignition zone. The conclusion is that the seats alone did not contain sufficient fuel for the fire to spread within the train, and instead there needed to be luggage in between the seats.

The results from fifth test suggest that not only the luggage is a key parameter for fire spread. When the test results were compared, the importance of the HPL boards mounted to the walls and ceiling above the ignition source was shown to be important. The vertical flames resulted in a higher radiant heat flux towards neighboring areas and the fuel further away was pre-heated to a higher extent. The conclusion is that combustible linings can strongly influence the fire development, even if these only are a small proportion of the entire fire load in the train carriage. This is also seen later in the full-scale tests, see chapter 3.4.

When the linings were very sparsely burnt the fire never developed into a flashover. The fire development is probably much more sensitive to the amount and disposition of the luggage in a train with non-combustible linings. Another aspect regarding the amount of fire load in the train carriage was seen when the fourth test and sixth test were compared. In the fourth test there was no luggage, but combustible seats with large exposed fuel surface area, while in sixth test the total weight of the luggage was 117 kg, yet both tests resulted in a flashover. The conclusion is that whether the fire reaches a flashover or not is more dependent on the fire growth in the ignition zone and its neighboring area rather than on the fuel load present further away.

In the cases where the initial fire did not exceed a range of 400 – 600 kW no flashover was observed. If the initial fire grew up to 700 – 900 kW, a flashover was observed. The maximum heat release rate during a short flashover period for this test set-up was about 3.5 MW. The time to reach flashover was highly dependent on the ignition type, i.e. two wood cribs with or without petrol.

For further information please read the full technical report and see the availability in Appendix:

- Claesson, A., Lönnermark, A., Ingason, H., Lindström, J., Li, Y. Z., and Kumm, M., "Laboratory fire experiments with a 1/3 train carriage mockup", SP Technical Research Institute of Sweden, SP Report 2012:06, Borås, Sweden, 2012.

Carried fire load

Trains and metros carriages in general meet high standards of fire protection of linings, train interior and electric cabling. A factor that is relatively uninvestigated and that in addition is difficult to control is the carried fire load the passenger's clothes, bags and luggage represent. Few systematic studies have been carried out regarding fire load and fire behavior for, for example bags, and few material data can be found in the literature, while the influence from for example surfaces is better documented. The connection between how much additional fire loads this represents, the expected energy contribution and how the material affects the total fire behavior was not either earlier investigated. The fire growth has far more importance for the evacuation than maximum HRR and increased fire load.

The influence of carried fire load at earlier occurred accidents

To investigate how the carried fire load have influenced the evacuation and fire development at earlier occurred accidents, two accidents with known outcome were studied more thoroughly; the fire in the Baku metro in Azerbaijan in October 1995 (Rohlén P, Wahlström B, 1996) and the Kaprun fire in Austria in November 2000 (Larsson S, 2004).

The fire in the Baku metro started in the electrical cables in carriage four in a set of five, travelling between the stations Uldus and Narimanov. The train carried approximately 1300 to 1500 passengers at the time of the fire. The train stopped, due to the fire in the electric cabelling, approximately 200 meters from the Uldus station and approximately 2 km from Narimanov station. The train and the tunnel close to the train were quickly filled with smoke, though the environment in the first three carriages was acceptable during the first five to ten minutes of the fire. An electric arc from the cable fire burnt off the pipes to the compressor tank underneath the train and created a welding like blaze that burnt through the floor into carriage four. The puncturing of the pneumatic tank lead to failure of the pneumatic driven doors and left the doors in closed position. The evacuating passengers pushed towards the sliding doors making them impossible to open. Some windows were broken in the early evacuation helping some passengers getting out of the train, but in the meantime filling the rest of the carriages with smoke. The fire in the fourth carriage made evacuation to the near-

by Uldus station more or less impossible for passengers in the first three carriages, who had to evacuate along the tunnel towards the more distanced Narimanov station. Due to re-direction of the ventilation during the accident, the smoke flowed over the majority of the evacuating passengers. Approximately 40 persons were found dead in the tunnel, about 25 persons in carriage four and five and approximately 220 persons in carriage one to three. In total 289 persons got killed in the fire and 265 were injured. The coaches were of Russian E-type with steel chassis and strengthen glass windows and doors of aluminum. The floor mate-rial was partly wood with a surface of linoleum, foam seats and laminated plastic as surfaces on walls and roof. The accident has many similarities with the fire at the Rinkeby metro sta-tion in 2005, but with a total different outcome.

The other studied accident, the fire in the mountain railway in Kaprun started in an elec-tric heater placed in the lower driver's cabin. A minor leakage of hydraulic oil provided the over-heated heater with fuel and contributed to the fast fire growth in combination with melted plastic details from the driver's cabin. The oil leakage, that also supplied the train's break system, stopped the train 600 meters inside the tunnel. It also made the hydraulic driv-en doors impossible to open from the driver's cabin. The tunnel is 3.4 km long and has an inclination of 45 degrees. Prior the accident the train was described as more or less incom-bustible. The fire in the mountain railway train started in an electric heater placed in the lower driver's cabin.

When the driver discovered the fire three minutes after the train turned to a halt inside the tunnel, he informed the guard at the mountain station about the fire and gets the immediate order to try to open the doors manually to save the passengers. The panic level rose among the trapped passengers and skiing boots and skis were used to try to break the windows to make evacuation possible. The train driver only succeeded to open a few doors. The fire de-velopment was very fast, partly depending on the location of the fire at the lower end of the train and the chimney effect in the tunnel, partly depending on the furnishing and left clothes and equipment. 155 people died in the fire, including the driver, one passenger in the train coming the other direction, located approximately 1200 meters from the top station, and three persons from the ski center at the top station. Only 12 persons succeeded to get past the fire and run downwards and by that surviving the fire.

Consequences of left luggage

In both described cases the left luggage and equipment have contributed to the fire load and to some extent to the fast fire development. At the occurred accidents, due to natural reasons, measuring equipment was not present as it would be during controlled fire tests. For the Kaprun fire the left skiing equipment alone would represent a fire load of 10,5 GJ, calcu-lating that the equipment for 161 passengers weighs 350 kg, weighted value for the heat of combustion is 30 MJ/kg as the main part of the equipment consists of plastic.

After the fire in the Baku metro Swedish observers got access to the burnt train, which meant that the train and the left luggage could be documented. A photo sequence shows how the furnishing, including the surfaces and left luggage, were affected in the totally burnt out coach 5, the, to a great extent, burnt out coach 4 and the essentially unaffected coaches 1-3. It should be noted that the fifth coach was totally burnt out, but there was still combustible ma-

terial left in the fourth coach, where the fire started. An approximation, without consideration of the contents of the luggage, based on the picture taken by the Swedish observer team does within reasonable limits agree with the findings in the later performed Swedish field study.

Figure 3   Photos from the Baku metro coaches.
Photo: Per Rohlén.

Figure 4   The unaffected metro coaches.
Photo: Per Rohlén.

The Swedish field-study

To survey the occurrence and type of carried fire load in the metro and at the commuter trains in Stockholm A field-stud was performed between the 12th of April and the 28th of May 2010, with complementing visits in June 2010 after evaluation. The study was carried out through interviews, photo documentation and weighing of the passengers' luggage. The field-study was performed in cooperation between Stockholm Transport, the tunnel operator MTR and Mälardalen University.

For the study lines, times and days were chosen so that the result would be as representative as possible for all lines in the metro and at the commuter trains at different times. At the trains random passengers were asked if they wanted to contribute to the study and allow their bags to be weighed. They were also asked what material the content consisted of, their age in ten-year intervals and if they would allow the observer to take a photo of the bag. It was all registered together with the sex of the passenger, time and metro or commuter line. General photos were also taken to document how and where the luggage was kept during the travels. In addition it was noted what share of the passengers were carrying bags at different times.

During the study it was registered that some of the free newspapers that are distributed in the metro were left on the trains. Both for order and fire safety reasons the newspapers are continuously removed at the terminal stations. After the study it was controlled, by MTR and IL Recycling, which amount of newspapers are removed from the trains, or are placed in the METRO-recycling bins at the stations. In total approximately 14 tons of paper is recycled weekly, which divided by the trains at the morning rush hours is less than 10 kg per train. The additional fire load is then in average 170 MJ per train, which can be considered negligible.

On the commuter trains the occurrence of larger bags, roller bags and suitcases was higher than on the metro, where mostly handbags, middle sized bags of sport bag type or rucksacks were carried. On the commuter trains also bikes were brought more frequently, which only occurred as an exception in the metro. The bikes do not represent any larger fire load, but were for natural reasons placed close to the exits, which could influence the evacuation situa-

tion. The occurrence of prams was distributed relatively even between commuter trains and metro.

In total 323 bags in the metro and 299 at the commuter trains were examined. The occurrence of suitcases and other larger bags was higher on travel days, like Fridays, Sunday afternoons and Monday mornings as well as during the business hours on Saturdays. The occurrence of back-packer rucksacks can be expected to be higher during the tourist season and would then raise the average weight of the carried fire load.

The average weight of each carried piece of luggage constituting a fire load at the commuter trains were;
-weekdays 4,4 kg
-travel days and weekends 4,9 kg
-in total 4,65 kg

For metro;
-weekdays 3,5 kg

-traveldays and weekends 4,5 kg
-in total 4,2 kg

On the commuter trains approximately 87% of the passengers carried bags, while the corresponding value for the metro was 82%. In average two prams were brought per train set during 75% of the studied time (rush hours and daytime). 28% of the passengers asked (300 randomly asked) carried some sort of pressurized cans, like hairspray or other cans, mostly pressurized with flammable gas.

A train set in Stockholm can carry approximately 1200 passengers during rush hours. This implies that an additional fire load corresponding to 85 GJ can be present on the train. This was not accounted for when designing the trains and stations. The value was calculated with guidance of the weight distribution that was estimated during the study.

- 1200 persons of which 82% carried a bag of 4,2 kg
- Metal share is counted out and the rest distributed;

    -Electronics/plastic; 4133*0,17*35MJ/kg= 24 591 MJ
    -Textile/mix; 4133*(0,37+0,03)*20MJ/kg= 33 064 MJ
    -Paper/food; .; 4133*(0,31+0,06)*18MJ/kg= 27 526 MJ

Total contribution to fire load is 85GJ if newspapers, prams and passenger clothes, as well as possible human contribution, are excluded.

It should though be noted that in a real life fire situation not all of this luggage would be left on the train. Depending on the fire development in the early stages, the weight and individual importance of the luggage it will either be left or carried along during the evacuation.

Most frequent content (weight)

mix ■ electronics ■ textile ■ paper ■ plastic ■ metal ■ food and provisions

3%

6%

6%

11%

6%

31%

37%
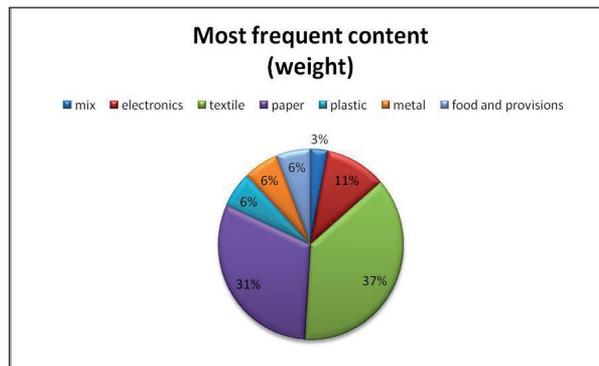
Figure 5   Distribution of content, in total metro and commuter train

Laboratory luggage fire tests

Based on the results from the field-study 11 representative bags and one pram were chosen for further studies. The bags were packed, based on the result from the field-study, and weighed. The weights were summarized in the categories metal, paper, plastics, textile, wood and other. As the study resulted in very little foundation for content of backpacker rucksacks that content instead was based on advice on backpacker homepages. The tests were performed in the large fire hall at the SP Swedish Technical Research Institute, during August 2010. As ignition source a pilot flame of 25 kW LPG in 90 s was used.

The tests were performed on the following items;
1) Laptop bag
2) Sports bag
3) Tourist bag
4) School bag – university
5) School bag – high school
6) Handbag
7) Suitcase
8) Cabin bag
9) Shopping bag (clothes)
10) Backpacker rucksack
11) Pram
12) A: Roller bag (with food) B: Paper carry-bag (with food)

All tests, except the roller bag that was not ignited by the pilot flame. The food was thereafter re-packed in paper carriers and the test remade. The weights allocated to the categories above and the measured remaining weights can be found in the full report.

The test objects were placed on a grid in the safety booth underneath the measuring hood. The tests were video filmed and CO, CO_2 and O_2 as well as the temperature in the hood was measured. Calculated heat release rate (HRR) was automatically registered in the measuring program based on the measured values in the hood, while the energy content was calculated

manually. The rest weights were measured and the material distribution estimated. HRR and energy content for all tests can be found in the full report. The HRR-curves for the five test objects with the highest heat release rates are shown below.
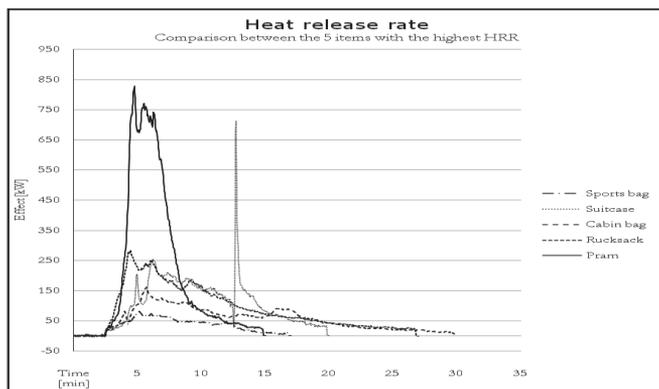
Figure 6   Comparison between the 5 items with the highest HRR (Peak HRR at 13 minutes represent explosion of pressurized can with hairspray)

Discussion and results

The performed study shows that the carried fire load in mass-transport systems underground can be considerable, especially at rush-hours. As a comparison the new Dehli metro, built after English fire safety standards, has a dimensioning fire load of approximately 160 GJ, though without front cone and some of the fittings in the driver's compartment. It shall though be noted that this train type only consists of steel passenger seats and in general have a slightly lower fire load than a train that operates in Stockholm. The carried fire load in a crowded metro train can be as much as up to approximately 50 % of the fire load of the train itself in this comparison. If the luggage is left on the trains it can become the factor that makes the fire spread and grow to flash-over. The increased fire load will also prolong the duration of the fire and influence the damage on the construction and the rescue services' possibilities to perform a successful rescue operation. If the luggage instead is carried off the train in an evacuation situation it could cause difficulties when dismounting the train to the track or obstruct the evacuation path if left behind along the way.

In addition the fire tests show that a pram alone can be at risk to cause local flash-over in a metro coach, as it in short duration develops 831 kW. A pram will of course not self-ignite and will constitute a hazard only if it is exposed to some sort of pilot flame like arson or if it is left in the metro coach after evacuation due to fire. The pram used at the fire tests was of 2010 model and can be considered representing modern prams well. A comparison of how easily textile samples ignite between the model used at the fire tests and three other comparable models showed no marked differences.

For further information please read the full technical report and see the availability in Appendix:

- Kumm M, "Carried Fire Load in Mass Transport Systems", Mälardalen University, Research Report SiST 2010:04

Full scale fire tests in the Brunsberg tunnel

The full scale fire tests were carried out in the Brunsberg tunnel outside Arvika in Sweden in September 2011. The tunnel was 276 m long tunnel and was taken out of service when a new tunnel was constructed close by to reduce the sharpness of a bend in the route. The cross-section of the tunnel varies along the tunnel but the average width was 6.4 m the average height was 6.9 m.

For the full-scale fire tests the project received two commuter train sets of the type X1, donated by the Stockholm Public Transport (SL). Each train set consists of one motor carriage and one manoeuvre carriage. In the fire tests, only the manoeuvre carriage from each train set was used, see Figure 7.

Figure 7   Trains of type X1 were used in the fire tests. Luggage was used in the tests

The maneuver carriage was approximately 24 m long. There was a driver's compartment at one end and the length of the passenger compartment was 21.7 m. The width of the inside of the carriage was 3 m and the height along the centerline was 2.32 m. The height at the wall was 2.06 m. The horizontal part of the ceiling was approximately 1.1 m wide.

During the full-scale test series, three fire tests were performed, one test with a fire initiated directly under the carriage and two fire tests where the fire was initiated inside the carriage. The latter two ultimately involved the entire carriage in the fire. For test 1 and test 2 the X1 train was used with original shape and material (see Figure 7), and the same carriage was used in both tests. The carriage used in test 3 was refurbished to be similar to a modern C20 carriage (used in the Stockholm metro). The seats were refitted using X10 seats (relatively similar to C20 seats) and the walls and ceiling were covered by aluminium, see Figure 8. Note that the old walls and ceiling materials were retained behind the aluminium lining.

Figure 8   Interior design of the X1 train that was refurbished to look like a C20 train inside

In test 2 and test 3, the ignited petrol in one corner of the carriage spread on the floor and to nearby luggage and other material. The initial development was similar in the two tests, but very soon the development differed significantly (see Figure 9). In test 2 the fire continued to develop very fast and soon the entire carriage was involved in the fire. The gases near the 0.29 m from the ceiling near the position of ignition reach a temperature of 600 °C after approximately 4 min. The corresponding conditions were reached in the other end of the carriage after approximately 11.5 min. In test 3, on the other hand, the initial development stopped and the fire spread slowed down. The fire did, however, not extinguish completely, but continued on a low and relatively constant level.

Since one of the aims of the fire tests was to study the effects (condition in the tunnel, radiation, etc.) of a fully developed fire it was decided to assist the fire development by igniting some additional pieces of luggage. Two litre of Diesel fuel was added to each of five pieces of luggage in the vicinity of door 1, i.e. 10 litres in total. However, when the first of these pieces of luggage (very close to door 1) was ignited approximately 110 min after the original ignition, the fire fighter igniting the luggage saw flames on the ceiling and had to exit the carriage without igniting the other prepared pieces of luggage. The fire had spontaneously spread to the driver's cabin. This then spread the fire back again to the passenger compartment shortly after the decision was made to intervene in the fire progress. The fast temperature increase (0.88 m from the driver's cabin; 0.29 m from the ceiling) started approximately 103 min after ignition. At the time 108.4 min the temperature in this position raised above 600 °C. At the time 103.8 min after ignition, the temperature was still higher in the driver's compartment than in the passenger compartment, but the flashover of the driver´s compartment did not occur until the time 105 min, i.e. after the temperature has started to increase in the passenger compartment, but before the passenger compartment was fully involved in the fire. At the time 110 min after ignition, the temperature near the ceiling inside door 1 was approximately 500 °C.
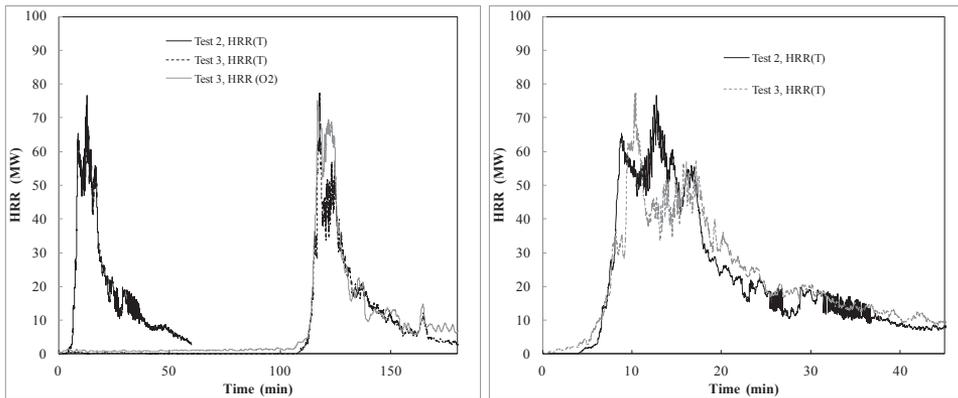
Figure 9 Left: HRR from test 2 and test 3 with real time scale. Right: HRR from test 2 and test 3 with the time scale in test 3 shifted.

Figure 10 Developed backlayering in test 2 (left) and large flames and progressing backlayering in test 3 (right).
Photo: Per Rohlén.

The fire development in test 3 after the fire spread to the passenger compartment was very similar to the one in test 2. The HRR curves are presented in Figure 9. In the left figure the curves are shown with the real time from the tests, while in the right figure the time scale for test 3 is shifted so that the time for the increase corresponds to the one in test 2. As can be

seen in the figure, the general shape of the two fire curves are almost the same, although the time for the maximum HRR is not the same. The maximum HRR in test 2 was calculated to be 76.7 MW (12.7 min after ignition), while the corresponding value for test 3 was 77.4 MW (117.9 min after ignition), i.e. in both tests the maximum HRR was calculated to be approximately 77 MW. Photos from Test 2 and Test 3 are shown in Figure 10.

The estimation of the total energy content in the material in the carriages is uncertain due to limited information on many of the materials. Integrating the HRR curves in Figure 9 can give additional information on the total energy. For test 2 the energy released during the first 60 min was approximately 64 GJ, while the released energy during the first 185 min in test 3 was approximately 71 GJ. Since the fires were not extinguished at these times the total energy content should be higher than these values.

The gas temperature inside the carriage reached approximately 1000 °C in both test 2 and test 3 and although the large difference in fire development, as discussed above, the temperature development for the parts when the entire carriage gets involved in the fire are similar to each other. In Figure 11 the period of initial fire spread in the beginning of test 3 is well illustrated reaching a long period of low and relatively constant temperatures before the start of the fast fire spread.
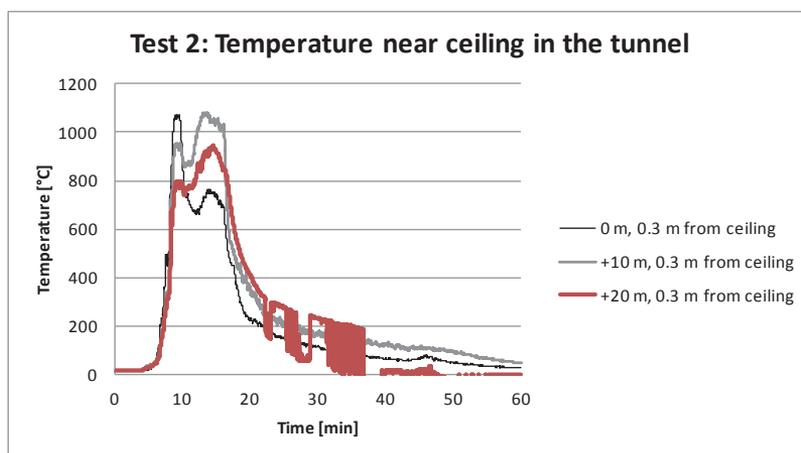
Figure 11   Gas temperature near the ceiling in the tunnel in Test 2

In the tunnel, the maximum temperature measured near the tunnel ceiling was approximately 1100 °C both in test 2 and test 3. However, the maximum temperature was somewhat higher in test 3: approximately 1120 °C measured above the centre of the carriage, while the maximum temperature in test 2 was approximately 1080 °C, measured at the position +10m (10 m downstream the centre of the carriage). The time resolved temperature results for test 2 are presented in Figure 11. The maximum temperatures in three positions above the carriage are summarized in Table 2. The gas temperatures near the ceiling in test 1 were not affected by the fire. A method presented by Li and Ingason (2012) was used to calculate the

ceiling gas temperatures in the tunnel. The method was found to work very well for the conditions tested.

Table 2   The maximum gas temperature near the ceiling above the carriage in test 2 and test 3

Test	Position -10 m (°C)	Position 0 m (°C)	Position +10 m (°C)
2	911	1073	1081
3	702	1118	980

The main reason for the difference in fire growth rate between these tests was due to the involvement of the combustible wall and ceiling lining in the test conducted in the old style X1 carriage. This would indicate that there is a greater opportunity for passengers to react to a developing fire in a modern carriage than in an old carriage.

The maximum HRR calculated from the experimental results are significantly higher than those obtained in other documented test series. The luggage in, under or between different seats is assumed to increase the fire spread significantly in both cases. Clearly, it is necessary for train owners to consider this transient load when conducting risks assessments and designing response tactics.

For further information please read the full technical report and paper and see the availability in Appendix:

- Lönnermark, A., Claesson, A., Lindström, J., Li, Y. Z., Kumm, M. and Ingason, H., "Full-scale fire tests with a commuter train in a tunnel", SP Technical Research Institute of Sweden, SP Report 2012:05, Borås, Sweden, 2012.

- Lönnermark, A., Lindström, J., Li, Y. Z., Ingason, H., and Kumm, M., "Large-scale Commuter Train Tests - Results from the METRO Project", Proceedings from the Fifth International Symposium on Tunnel Safety and Security (ISTSS 2012), pp. 447-456, New York, USA, 14-16 March, 2012.

Correlations between model and full scale fire tests

As shown in earlier chapters for WP1, three series of train carriage fire tests were carried out in different scales according to the Froude scaling which has been further developed by SP. Earlier Ingason (2005) carried out railcar fire tests in scale 1:10. In the following analysis the tests included are; 1:10 model scale tests, 1:3 model scale tests, 1/3 laboratory mock-up tests and full scale tunnel tests.

The mechanisms of fire development in all the tests are very similar. The spread of the fire from the initial location strongly depends on the fuels beside, such as luggage and combustible wall panels. Only if the initial fire size reaches a certain level, the spread to the neighbouring targets could occur. In such cases, the fire behaves as a travelling fire at the beginning then transfers to local flashover fires after the gas temperature in the hot gas layer ex-

ceeds around 600 ºC - 800 ºC, and the fire starts to spread rapidly until finally the whole carriage gets involved in the combustion. In such types of fires, the fire tends to be ventilation controlled due to limited openings.

The maximum heat release rate in these tests generally can be estimated based on fully consumption of the oxygen flowing into through the openings multiplying by a correction factor, which ranges from 0.6 to 1.7 and is around 1.25 in full scale tests. Note that the 1/3 laboratory mock-up tests are fuel controlled and were extinguished after the fire reaches over 3 MW.

In all the tests with fully developed fires, the maximum gas temperatures inside the carriages are around 1000 ºC and the temperature difference between different heights disappears. At the beginning, the ceiling temperature decreases with the distance away from the initial fire source but the difference decreases with time. The position of the maximum ceiling temperature in the carriage moved from the initial fire site to the further positions during the tests since the fuels close to the initial fire source had consumed when the further positions were fully involving in the combustion. This indicates the characteristics of local flashover in a carriage fire.

Table 3   **Summary of gas concentrations measured in different tests**

Test series	Ceiling level			Middle height			Floor level		
	O_2	CO_2	CO	O_2	CO_2	CO	O_2	CO_2	CO
	%	%	%	%	%	%	%	%	%
1:10 model scale	0	>10	>3	–	–	–	–	–	–
1:3 model scale Test 5	0	~22.5	>10	0	>10	>3	–	>10	>0.4
1:3 model scale Test 10	0.02	18.8	9.3	0.02	>10	>3	–	>10	>0.4
1/3 full scale	–	–	–	–	–	–	–	–	–
Full scale Test 2	3.2	14.0	8.5	9.1	8.2	5.2	0.8	17.5	9.3
Full scale Test 3	8.5	9.3	2.3	8.0	8.6	4.3	0.07	17.5	~10

The gas concentrations in these carriages show high similarity in different scales, see Table 3. All the minimum measured O_2 concentration is around 0. The oxygen was reduced from 21 % to 0 in 1:3 model scale Test 5 and Test 10 and 3.2 % in full scale Test 2. The CO concentration was 9.3 % in 1:3 Test 10 and 8.5 % in full scale Test 2. All CO_2 concentrations range from 8 % to 22.5 %, regardless of its location and test series. In reality, the gas concentrations indicate the combustion conditions at the specific location. Although only the maximum values were compared and discussed, it can be concluded that the extreme values of O_2, CO_2 and CO concentrations were close to each other and the combustion behaviours are similar in all these tests with fully developed fires.

4 WP2 – Evacuation

The definition of a safe underground rail transportation system heavily relies on the possibility to evacuate it in case of fire. In this respect, an underground rail transportation system is no different from a traditional building. However, the often complex and unfamiliar underground environments, which may be hard to overview for occupants, bring forward a number of especially important factors that need to be addressed in the fire safety design of these types of constructions.

A potentially severe event is when evacuation is required from a train inside a tunnel due to fire. Although the general principle is to move a train on fire to the nearest station and there disembark its passengers, previous devastating fires in for example Zürich in Switzerland (1991), Baku in Azerbaijan (1995) and Kaprun in Austria (2000), demonstrate that this is not always possible and that passengers from time to time are forced to evacuate inside the tunnel. This is an event that can be expected to be particularly difficult, if not impossible, for children, senior citizens and people with disabilities. It is also a situation that most likely involves movement through smoke sometime during the evacuation process. Therefore, the focus of the second work package (WP2 – Evacuation) has been to study these types of events in detail.

Literature review of accidents and empirical research

In the first step of WP2, a literature review was performed, including essentially three areas: (1) general theories and models on human behavior in fire, (2) past fires in underground transportation systems, and (3) previously performed research in the field of evacuation in underground transportation systems. All aspects related to evacuation were considered, and the main purpose was to provide guidance to engineers involved in the fire safety design process of underground transportation systems. The current theoretical framework on human behavior in fire was analyzed and modified to enable an application to underground transportation systems, and the past fires were analyzed based on this framework.

Based on the literature review, it is concluded that human behavior in fire is complex and that it sometimes can seem irrational to a person studying the behavior in retrospect. But instead of using the term 'panic' to describe the human behavior in, and the outcome of, an accident, the adoption of a clear theoretical framework will aid the understanding of the behav-

ior. It is recommended that four main theories are used, namely (1) the behavior sequence model, (2) the affiliative model, (3) social influence and (4) the theory of affordances.

One of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate an evacuation. This is explained by a number of factors:

- That people tend to maintain their roles (e.g., as passengers)
- The lack of fast, clear and coherent information
- The ambiguity of the cues from the source of danger (e.g., a fire)
- The presence of others, i.e., social influence.
-

Furthermore, when an evacuation has been initiated there are other factors that affect the efficiency of the evacuation. Some of the problems that were identified are:

- Problems with the door-opening mechanism on trains
- The vertical distance between the train and the tunnel floor
- That people tend to evacuate through familiar exits
- Lack of lighting
- Uneven surfaces inside the tunnels

Apart from the aspects presented above, many potential solutions to commonly observed evacuation problems were studied in the literature review. Also, future research needs were identified.

For further information please read the full technical reports and papers and see the availability in Appendix:

- Fridolf, K. (2010). *Fire evacuation in underground transportation systems: A review of accidents and empirical research*. Report 3151. Lund: Lund University.
- Nilsson, D., & Fridolf, K. (2010). Utrymning av tunnelbanor: Faktorer att beakta vid utformningen av brandskyddet. *Bygg & Teknik*, (6), 45-48.
- Fridolf, K., Nilsson, D., & Frantzich, H. (2011). Fire evacuation in underground transportation systems: A review of accidents and empirical research. *Fire Technology*. doi:10.1007/s10694-011-0217-x.
- Fridolf, K., Nilsson, D., & Frantzich, H. (2012). Taking advantage of theories and models on human behaviour in the fire safety design of underground transportation systems. In *Proceedings of the fifth international symposium on tunnel safety and security*. New York City, USA.

Questionnaire study

Parallel to the literature review, described above, a questionnaire study was carried out with the main purpose to collect information related to the fire protection of underground rail transportation systems in different countries. Out of thirty representatives, seven replied to the questionnaire, which included questions related to typical underground stations, safety

instructions and excercises, and technical systems, installations and equipment. The respondents were, in addition, asked to give their recommendations and suggestions for future research, based on their own experience. The result of the questionnaire study were presented together with a brief discussion on how the respondents' answers related to generally accepted theories and models on human behavior in fire, and is in essence available in Fridolf, & Nilsson (2012) at http://www.metroproject.se/publications.html:

- Fridolf, & Nilsson. (2012). *A questionnaire study about fire safety in underground rail transportation systems*. Report 3164. Lund: Lund University.

The full questionnaire is available at the following web page:

http://www.metroproject.se/questions

Small scale experiments

During the work with the literature review and the questionnaire study, described above, one certain event stood out as particularly interesting to study in detail from an evacuation perspective, namely the evacuation of a train inside a tunnel. The event includes a number of potential bottlenecks, in terms of obstacles where the flow rate of people may be severely restricted. Furthermore, due to the fact that more "vulnerable" people, e.g., people with disabilities, will use the public transport system in the future (due to accessibility design improvements of the underground rail transportation system as a consequence of the ninth article of the Convention on the Rights of Persons with Disabilities which was adopted by the United Nations General Assembly on December 13th, 2006), another dimension of complexity is added to the event.

A small scale lab experiment was therefore performed to study the relative importance of different train exit configurations, i.e., train exit designs, on the flow rate of people and their perceived ability to exit the train in an evacuation situation. The experiment was performed in an experimental rig, constructed out of aluminum profiles and particle board, with corresponding dimensions of the cross section of a real train (Figure 12 and Figure 13).
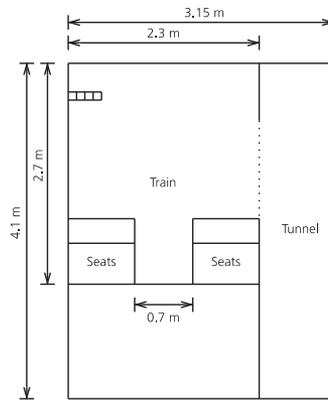
Figure 12   A drawing of the experimental rig (side view)
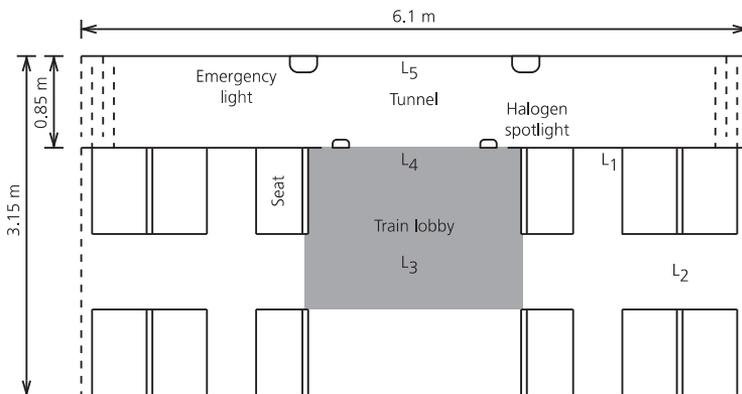
Figure 13   A drawing of the experimental rig (top view)

Due to ethical reasons, more specifically to minimize the risk of injuries for the "vulnerable" people in the experiment, it was divided into two parts: (1) a flow rate experiment with students at Lund University, and (2) an interview study with senior citizens and people with disabilities.

In the flow rate experiments, the following variables were changed in order to study their impact on the flow rate: (1) floor material inside the tunnel, (2) train exit height, (3) presence of an emergency ladder in the train exit, (4) lighting conditions inside the tunnel or (5) presence of extra handles in the train lobby. The result shows that the train exit configuration will have an impact on the flow rate of people in an evacuation situation, although not very high in terms of relative comparisons of the flow rate of people. More importantly, the population

density in the tunnel, i.e., the crowdedness in the tunnel, seems to limit the flow rate of people in the train exit.

The interview study revieled that the train exit configuration will be very important for the "vulnerable" population, e.g., people with disabilities, children, elderly and unfit people. If this population are to be able to evacuate at all in a tunnel, the height difference between the train and tunnel floor needs to be lowered from todays 1.4 meters (in the Stockholm Metro), or a technical installation, such as an emergency ladder, needs to be installed. For more details and information on the flow rates of people, suggested train exit designs, and more, the reader is referred to the following literature. For further information about the availability see Appendix:

- Grindrod, Welch, & Fridolf, K. (2011). A priori modelling of an underground evacuation. In *Proceedings of advanced research workshop: Evacuation and human behaviour in emergency situations*. Santander, Spain.
- Fridolf, K., Nilsson, D., & Frantzich, H. (2012). The flow rate of people during train evacuation in rail tunnels: Effects of different train exit configurations. *Manuscript submitted for publication*.
- Fridolf, K., Nilsson, D., & Frantzich, H. (2012). Train evacuation inside a tunnel: An interview study with senior citizens and people with disabilities. In *Proceedings of the fifth international symposium on human behaviour in fire*. Cambridge, UK: Interscience Communications.

Medium scale experiment

As a continuation of the event in which train passengers are forced to evacuate a train inside a tunnel, the medium scale experiment of WP2 was performed as a field experiment in Stockholm. The purpose was mainly to study human behavior, movement speeds and exit choice for a heterogeneous population. One hundred participants took part in the experiment and all evacuated a 200-meter long smoke filled tunnel with different technical systems (see Figure 14).
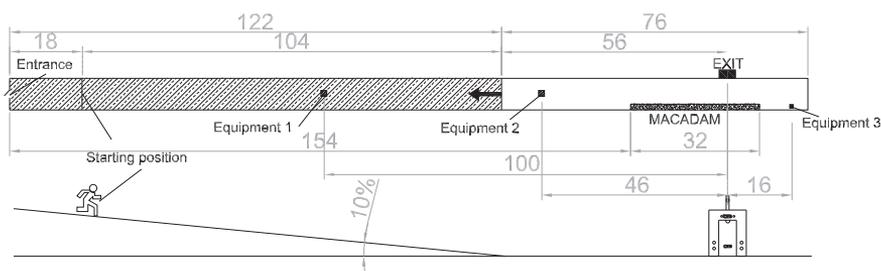
Figure 14   A drawing of the tunnel used in the medium scale experiment
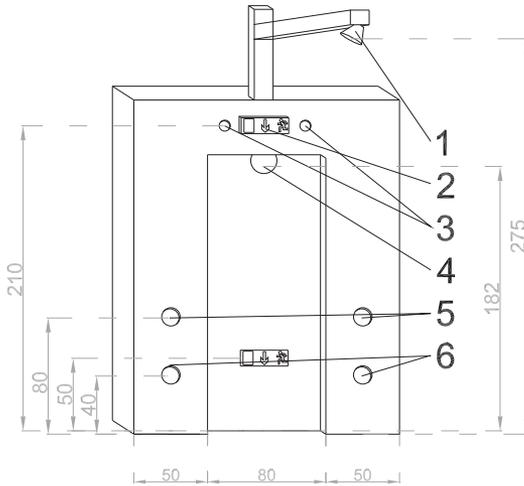
Figure 15 A schematic drawing of the emergency exit inside the tunnel (measurements in centimetres)

Figure 16 A picture of the emergency exit inside the tunnel

Table 4   A description of the different way-finding installations at the emergency exit

Installation	Description
1. Halogen lamp	A white halogen lamp of 500 W installed above and directed towards the door. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 556 lux, measured 22 cm from the lamp.
2. Emergency exit sign	Standard backlit European emergency exit sign.
3. Green flashing lights	Green flashing lights, which consisted of two green light bulbs, installed on each side of the emergency exit sign above the door. The lights flashed with a frequency of approximately 1 Hz, i.e., one flash per second.
4. Loudspeaker	Loudspeaker installed on the upper centre part of the door enabling an alarm signal and a pre-recorded voice message to be broadcasted. The alarm signal consisted of an increasing signal, which was repeated three times within 1.5 seconds [35]. The frequency range was 800-970 Hz. The alarm signal was repeated twice before the pre-recorded voice message; a computer generated female voice that said (translated from Swedish): *The sound is coming from an exit. Follow the sound in order to get out.*

	The alarm signal and voice message could be heard approximately 25 meters from the door.
5. Green lights	Green light bulbs installed on each side of the door on the lower part of the frame.

Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 11 lux, measured 20 cm from the bulb. |
| 6. White lights | White light bulbs installed on each side of the door on the lower part of the frame.

Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 63 lux, measured 20 cm from the bulb. |

Table 5   The experiment scenarios

Scenario	Way-finding installations
1	2
2	2,3
3	1,2,5,6
4	2,4
5	1,2,3,5,6

An emergency exit was placed 180 meters into the tunnel. This exit was equipped with different way-finding installations according to Table 4, as well as Figure 15 and Figure 16. These installations were tested in specific combinations to achieve different designs of the exit, i.e., the experimental scenarios according to Table 5.

Exclusive data, particularly valuable in evacuation analyses of underground transportation systems, was retrieved and has filled a great gap of knowledge in the field of tunnel evacuation. In essence, the participants moved with an average of .9 meters per second in the smoke filled environment (average visibility of 1.5-3.5 meters). No effects of fatigue or learning were possible to detect. In particular, a way-finding installation at the emergency exit, which consisted of a loudspeaker (see scenario 4 in Table 5), was found to perform particularly well in terms of attracting people to the door. Other installations consisting of light combinations was not as good, and some even repelled the participants due to the fact that they were perceived as trains, gearshifts, or other track related installations (see scenario 3 and 5 in Table 5).

For more details on movement speeds, human behavior activities during the evacuation and exit choice, the reader is referred to the following literature. For information about the availability see Appendix:

- Fridolf, K., Ronchi, E., Nilsson, D., & Frantzich, H. (2012). Movement speed and exit choice in smoke-filled rail tunnels. *Manuscript Submitted for Publication*.

- Nilsson, D., Fridolf, K., & Frantzich, H. (2012). Design of evacuation systems in underground transportation systems. In *Proceedings of the 5th human behaviour in fires international symposium.* Cambridge, UK: Interscience Communications.
- Fridolf, K. (2013). Evacuation experiment in a smoke filled tunnel. Work in progress. Lund: Lund University.

Full scale experiment

On the night between the 7 and 8 of November 2012, a full-scale evacuation experiment including over 300 participants was supposed to have been carried out in the Stockholm Metro system. However, due to different reasons not listed here the experiment had to be cancelled. At the time of when this text was composed, there were still ongoing activities in trying to establish a new date for the full-scale evacuation experiments. The aim is to perform the full-scale experiments in spring 2013.

Engineering tools for evacuation modelling

One of the aims of WP2 was to develop engineering tools for evacuation modeling. Although no computer software has been developed, underlying relationships for evacuation modeling have been established and incorporated in existing models. For example, a model for comparing different train exit design was developed after the small-scale experiment, and a model for expressing the movement speed as a function of the visibility, i.e., the light extinction coefficient, for people evacuating smoke filled tunnels was developed after the medium scale experiment. These tools are available in the following literature. For information about the availability see Appendix:

- Grindrod, Welch, & Fridolf, K. (2011). A priori modelling of an underground evacuation. In *Proceedings of advanced research workshop: Evacuation and human behaviour in emergency situations.* Santander, Spain.
- Fridolf, K., Ronchi, E., Nilsson, D., & Frantzich, H. (2012). Movement speed and exit choice in smoke-filled rail tunnels. *Manuscript Submitted for Publication.*
- Fridolf, K. (2013). Evacuation experiment in a smoke filled tunnel. Work in progress. Lund: Lund University.
- Fridolf, K., Nilsson, D., & Frantzich, H. (2012). The flow rate of people during train evacuation in rail tunnels: Effects of different train exit configurations. *Manuscript submitted for publication.*

5   WP3 – Integrated Fire Control

The Stockholm Public Transport – SL – is the main funder of the METRO-project. SL has 53 ground level stations and 47 stations under ground. The metro system consists of 105 km metro track of which approximately half is located in underground tunnels. The Stockholm Metro has more than 1,2 million boardings every day, the year around. The main objective for SL to participate in and contribute to the METRO-project has been to gain knowledge that can be used in the systematic fire prevention work and as safety basis in procurements for future station, trains and tunnels. SL has during the duration of the project reorganized from mainly being a performance based organization with all vital functions in-house to becoming an organization with outsourced functions of operating traffic, station and escalator maintenance and as from February 2013 also the infrastructure itself, such as tracks, stations and tunnels will be outsourced.

Questionnaire and literature review regarding the interaction between technical and organizational fire safety

In cooperation between SL and Mälardalen University a questionnaire regarding the collaboration between European capital fire services within the European Fire Services Tunnel Group (EFSTG) and metro operators within their juridistiction. The main focus of the questions have been in the field occurrence and function of active and passive fire protection, contingency planning, organizational measures and how the different organizations use incidents and accidents to prevent future fires.

The results from the literature survey and the questionnaires are a base for the developed fire safety evaluation forms that will be implemented after the research parts of the METRO-project. The work has been performed as a Bachelor Thesis, which will be presented in the spring 2013.

- Karlsson, M., "The interaction between technical fire safety installations and organizational fire safety measures in underground metro systems- A study of systematic fire prevention at Stockholm Public Transport", Bachelor Thesis, Mälardalen University, 2013

Technical visits

During the three-year project personnel from SL have visited colleagues from Oslo metro, New York metro, London Underground, Budapest metro, Munich U-bahn, Frankfurt metro and the metro in Milano. At the visits safety and security issues have been discussed and the technical fire safety systems observed. Some of the visits have been performed in cooperation with the participating universities and some with only SL personnel. The technical descriptions of the visited metro operators can be found in the travel descriptions.

- Åkerstedt R, Ojala T, Technical Visits within the METRO-project, Stockholm Public Transport, Dnr SL-2012-04530, 2012

Learning from incidents and accidents

Both the Swedish Working Environment Act (1977:1169) and the Swedish Civil Protection Act (2003:773) contains part of systematic safety work with different degrees of. After the Rinkeby fire in May 2005 the Swedish Accident Investigation Authority pointed out the need of coherent safety governance in tunnel systems with more than one operator or entrepreneur (SHK, 2009). In connection to the re-organization of SL an internal project was started in order to monitor and learn from occurred incidents and accidents. At today's date the information have been collected but the analyzes still remain to perform. During the spring 2013 a new method for learning from incidents and fires in the Stockholm Metro will be evaluated and adapted to tunnel environment conditions and tried out in the new organization (Kjellén, 2000).

Implementation of results after the METRO-project

In the beginning of 2013 the last part of the METRO-project will be performed. This part only includes the Stockholm Public Transport and has to be performed without the close support from the other project members. The frame of the project has given possibilities to discuss, try out and learn over the organization borders. With a large multi-disciplinary project like METRO the results need to be implemented in many parts of the organization. One of the greatest challenges after the METRO-project is to find the internal paths that keep the knowledge from the project alive and administer the assets from the project wise and sustainable. To gain the most out of the project the results have to be implemented at all levels in the organization and continuously developed in order to keep up to date. One good example of practical use of results from the METRO-project is the analysis of a concrete column's capacity to withstand fire at Hötorget metro station, based on the results from the full-scale fire tests.

- Andersson, A., Carlsson, ES., "Structures in Underground Facilities – Analysis and Dimensioning of a Concrete Column's Capability of Withstanding Extraordinary Fire Loads", Master Thesis, Mälardalen University, 2012

6   WP4 – Smoke Control

Research into fire and underground facilities has increased over the last ten years, with the main focus having been on fire in tunnels. In buildings or other types of construction work there should always be a possibility of two-way escape exits. A number of metros in Europe today have stations with only one exit. The purpose of the work presented here is therefore to analysis specific problems in metros with single-exit stations. The overall objective is to investigate smoke control systems in single-exit stations. A fire in a single-exit station could be catastrophic, since the only way out could be blocked by the fire. One alternative to a second exit, which in existing cities could be very expensive and complicated, is a smoke control system combined with extinguishing system which secure the only exit. The purpose of the smoke control system is to remove smoke or to clear the exit from smoke to secure evacuation. The WP 4 has therefore focused on different systems for smoke control systems for single-exit stations. Input data has been provided by the results of the full-scale experiments performed in WP1, combined with results from performed model tests.

Smoke control systems for underground stations

The project was started with a study of the literature relating to smoke control systems in underground installations having only one emergency evacuation route. The results were presented to, and discussed with, scientists working on the project. Based on these discussions, two smoke control systems were selected for more in-depth analysis by CFD, using heat release rate input data based on results from WP 1. A large number of simulations were run. The reason for the large number of runs was to attempt to optimize the air flow rate in relation to the heat release rate and to the criteria that had been applied.

The literature study shows that there have been two principles of smoke control systems in underground stations: thermal and mechanical smoke ventilation, with mechanical ventilation being the most common. The drawback of thermal smoke ventilation is that it is sensitive to air currents and that evacuation routes from the underground station can become smoke-filled. Mechanical smoke ventilation can be arranged in various ways: by positive-pressure pressurization, by exhaust air abstraction over the track area, or by use of the tunnels themselves as exhaust air routes. A further possible way of improving the situation in a fire in an underground facility is to utilize platform screen doors, which provide additional separation with openings aligned with the train doors. The prime purpose of platform screen

doors is to improve comfort and environmental conditions for passengers, in terms of reducing particulates and elevated temperatures, but they could also contribute to improved fire protection.

Model scale fire ventilation tests

Model scale experiments were carried out in SP's facilities in Borås, using a model of an underground station with only one exit. The model was about 12 m long and about 1 m wide, on a scale of 1:20. It was based on the Zinkensdamm underground station in Stockholm, which provides a good example of an underground station with only one entrance/exit and two platforms linked to each other at one point via a platform-level stairwell/escalator lobby.

The purpose with the model scale tests is to examine the effectiveness of various smoke control systems and to receive input data to the CFD modeling. The model consisted of two platforms and two track areas, in one of which latter the fire was simulated. An inclined tunnel, representing the escalator shaft, was connected to the platforms. The trials also included platform screen doors to separate platform and track areas. The two smoke ventilation methods that were used were pressurization via the escalator shaft, powered by a fan, and an exhaust air system above the tracks. In the pressurization trial, air was blown down the escalator shaft and into the platform-linking lobby at the bottom. From here, it was discharged via the two door openings on each side to the two platforms. In a few cases, one of the doors to the platform not exposed to the fire was shut: in the other cases, all four doors from the escalator bottom lobby were open.

The results showed that both smoke control systems works to prevent smoke from entering the lobby and escalator shaft. The criteria was the temperature increase in the lobby. The experiment showed that the thermocouples were affected by conduction through the model construction which was made of stainless steel. The higher fire effects were problematic because the exhaust ducts became very hot and were close deformation.

During the experiments, it was found that the flow measurements were unclear; there were some uncertainty with respect to the flow measurement results (which was later confirmed with the CFD simulations). But an assessment of the results, converted to a full scale situation, shows that a pressurizing supply air system for a 20 MW requires a minimum of 20 m³/s and with a 60 MW fire about 30 m³/s. With mechanical exhaust air system (converted to full scale) 50 m³/s is required at 20 MW fire and 100 m³/s with the 60 MW fire.

These values were used as very rough initial values for the CFD simulations. The later performed CFD simulations show that the flow measurements in the model tests were probably underestimated. But the model scale tests worked as a good foundation and a good complement to CFD-calculations. In the experiments, it was found that at low air flow rates the conditions were under ventilated. These conditions cannot be replicated in the CFD model.

CFD calculations of smoke control in single exit stations

Two different smoke control systems, with two different configurations, were investigated, based on the results of a study of the literature:

- A pressurizing (positive pressure) supply air system;
- A pressurizing (positive pressure) supply air system, with platform screen doors;
- A mechanical exhaust air system, with extraction fittings above the track area; *and*
- A mechanical exhaust air system, with platform screen door.

Simulations were performed using FDS (Fire Dynamics Simulator), and investigating two different heat release rates, 20 MW and 60 MW. The calculations have investigated the conditions occurring at maximum heat release rates. All train doors, and doors from the escalator shaft bottom lobby to both the platforms have been assumed to be open. No allowance has been made for the effects of initial air currents, e.g. from trains. In FDS, the total calculation volume is divided into a large number of cells, or grids, for which the selected continuity equations are solved. In this case, a grid size of 0,20 x 0,20 x 0,20 m was used.

In all fire protection technical projects, it is necessary at an early stage to decide what is to be achieved. In this particular case, the initial criterion has been that the escalator bottom lobby must be kept clear of smoke. No allowance has been made for conditions on the platforms concerned. Other criteria could be considered: e.g. to keep the escalator shaft clear of smoke, or limiting the temperature on the platform to some maximum value, or maintaining a certain minimum visibility. The choice of criteria will affect the design and capacity of the fire gas control system.

In the same way as in the model scale trials, the model takes the Zinkensdamm underground station in Stockholm as its basis. The station has two platforms, 164 m long and 4,4 m wide. The two platforms are connected via the escalator bottom lobby, with two doors, 2,0 x2,4 m, to each platform, i.e. a total of four doors (see Figure 17). The inclined escalator shaft opens into the lobby with a cross-sectional area of 7,2 x 4,0 m. The vertical rise from the lobby level is about 10,0 m. The train consists of three cars, each 50 m long and 3,0 m wide. The track zone is 3,6 m wide, at a level of 1,4 m below platform level. All train doors are assumed to be open: door size is 2,0 x 2,4 m. Both platform tunnel sections merge on each side of the station: the two platforms are thus joined via the shared tunnel section.

The train (blue) is behind the yellow platform screen door. The fire is in the carriage closest to the escalator bottom lobby (also blue). All the doors to the lobby are assumed to be open on both platforms, and all the train doors are also open. In the pressurization cases, air flow is assumed to be evenly distributed across the upper part of the section of the escalator shaft.

The fire was assumed to be in one half of the central carriage, with an area of 24 m², based on the model scale tests. It was only the maximum heat release rate that was investigated. In the model, the fires were assumed to reach their maximum heat release rate after one minute. Two fires were investigated: 20 MW and 60 MW, with the model using respective specific heat release rates of 833 kW/m² and 2500 kW/m² for the two fires.
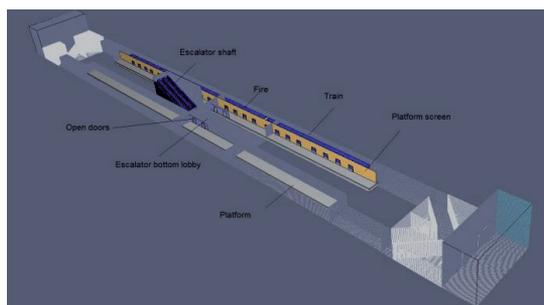
**Figure 17   Schematic picture of the CFD model, showing platform screen doors (yellow).
For clarity, certain walls are not shown in the picture.**

The results show that both the pressurizing supply air system and the mechanical exhaust air system provide effective fire gas control. Two fires were simulated in the work: a 20 MW fire and a 60 MW fire. The required performance criteria were to keep the escalator bottom lobby free of smoke. To do so with a pressurizing supply air system requires an air flow of 40 m³/s for a 20 MW fire, and 80 m³/s for a 60 MW fire. A mechanical exhaust air system requires considerably higher air flows: 100 m³/s to deal with the 20 MW fire, and 180 m³/s for the 60 MW fire.

If some doors at the bottom of the escalators are assumed to be closed (e.g. by automatic door-closers), the necessary air flow to control the gases in the pressurizing air supply air flow scenario will be reduced. However, some of the commonest automatic door closing devices can be sensitive to smoke detection, which means that they could open when they ought to be closed. The simulation calculations have also assumed that the doors in the platform screen doors are open. If they are assumed to be partly closed, this would probably also affect the fan capacities. The simulations have not considered air currents caused by trains, ambient wind conditions or temperature/height differences.

In the simulations the platform screen doors were only installed on the fire affected side. If the screen doors would be installed on the non-fire affected side, the situation on this side concerning smoke would most likely improve.

Table 6 presents the advantages and disadvantages of the two different smoke control systems.

Table 6   Advantages and disadvantages of the two different smoke control systems

System	Advantages	Disadvantages
Pressurising supply air system	Relatively simple to install in existing stations etc.	Does not extract smoke from the running tunnels: long lengths of tunnel can suffer from smoke
	Requires no duct systems	
	Requires lesser air quantities	Smoke can reach the other

	than a mechanical exhaust system	platform
		Mixed smoke layer
Mechanical exhaust ventilation system	An effective system that extracts smoke from the tunnel system.	Large air quantities required
		A system of air ducts is required
	In comparison with the pressurizing system, lesser areas are affected by smoke	

The choice of criteria for control of the spread of smoke and temperatures is decisive in determining the capacity of a smoke control system. If, for example, the criterion for a smoke-free escalator bottom lobby had been for a smoke-free escalator shaft, the necessary fan capacity would have been considerably less.

For further information please read the full technical report and see the availability in Appendix:

- Nyman, H. and Dittmer, T., (2012), Metro, WP4 – CFD-simulations of a single exit underground station, Report SiST 2012:04, Mälardalen University, Västerås.

- Nyman, H., Dittmer, T., Lönnermark, A., and Gehandler, J., Model scale test of a single exit underground station, SP Report 2012:61.

7 WP5 – Extraordinary Strain on Constructions

WP 5 concerns analysis of explosion scenarios in an underground train coach. It comprises inventory of occurred incidents from such scenarios and possible details described, but also a compilation of previous experimental and analytical work on explosion in tunnels. Furthermore it comprises experimental, analytical and numerical simulation work to determine the blast loads from explosions in different situations and the response of structures and humans.

The work includes the following parts; inventory of incidents and acts of explosion sabotage, studies of previous theoretical and experimental work with explosions in tunnels, calculation of blast load, small scale blast load tests, calculations of structural response, testing of vital components response to blast and a full scale explosion test.

Discussion with conclusions and recommendations based on the WP 5 results is presented in chapter 10 and 11.

Occurred explosions in mass transport systems from a social science perspective

The summary presented in this chapter is based on the CRISMART literature review of terrorist explosions on trains or subways that occurred over the ten year period, from 2000-2010, conducted within the METRO project. The following cases of train or subway explosions have been studied[1]: Moscow 6 February 2004; Moscow 29 March 2010; Madrid 11 March 2004; London 7 July 2005; and Mumbai 11 July 2006. Concise overviews of the aforementioned attacks are provided herein, followed by some brief points on trends in modus operandi in subway terrorist attacks. In conclusion, some general lessons learned regarding crisis preparedness, mitigation and response are provided.

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[1] There are several other terrorist incidents in recent decades where trains and/or passengers were targeted that are worthy of study but are beyond the scope of this short review, for example the 20 March 1995 Aum Shinrikyo sarin gas attack in the Tokyo subway and the Russian train bombings in Pyatigorsk on 3 September 2003 and in the Stavropol region on 5 December 2003.

Moscow 6 February 2004

A male suicide bomber, allegedly associated with Chechen rebels, detonated a bomb on a subway train about 500 metres from the station, killing 41 people. The bomb might have been placed in a backpack, or in a briefcase. More than 120 people were injured, suffering not only trauma/blast and burn injuries, but also smoke inhalation injuries – the latter posing a particular problem in underground attacks should fires ensue. Shortly after the attacks a Chechen militant group calling themselves "Gazoton Murdash" released a statement assuming responsibility for the attack (Gupta, 2011).

Moscow, 29 March 2010

On 29 March 2010, two female suicide bombers discharged explosive belts on subway trains during the morning rush hour, killing 37 and injuring more than one hundred. The first suicide bomber discharged her bomb at Lubyanka Station on the Sokolnicheskaya Line, which was strategically and symbolically significant as it is "located near the central headquarters of Russia's Federal Security Services (FSB)" (Gupta, 2011:11). In response to the first attack, the authorities detained the train that the second suicide bomber was on for 40 minutes between Frunszenskaya and Park Kultury stations, and she detonated her charge first when the train opened its doors on the platform to Park Kultury station (Ibid.). The belts were a combination of explosives and metal shrapnel (DHS, 2010).

Madrid 11 March 2004

On 11 March 2004, ten bombs exploded almost simultaneously in four commuter trains during morning rush hour in Madrid, Spain, killing almost 200 people instantly and injuring more than 2000. Subsequently, 14 people died at hospitals due to their injuries (Gutierrez 2005). In addition to the 10 bombs that exploded, three of four bombs failed to go off and were later deactivated by explosives experts (New York Police, 2008:8). The attacks were apparently planned and carried out by a Moroccan group linked to al Qaeda but they are not believed to have received "traditional training in terrorist camps abroad" (New York Police, 2008:8). The bombs were "pre-positioned on trains and placed in sports bags and backpacks" (New York Police, 2008:8). Each bomb bag was reported to consist of a Mitsubishi Triumph mobile phone, a copper detonator, 8-12 kilos of explosives, and metal fragments. Each mobile phone was pre-set to alarm at a designated time and set on vibrate mode. Wiring a mobile phone alarm circuit to an explosives detonator in this fashion. The first units of police and rescue personnel arrived at the sites at around 08:00, alerted by the CCTV operators at the stations. With as many as 2000 wounded, the rescue operation was seriously strained. Almost 300 ambulances were used, and many thousands of emergency workers were engaged. A field hospital was set up at a nearby sports center.

London 7 July 2005

Unlike the remotely detonated devices used in the Madrid attacks, the attacks in London on 7 July 2005 were conducted by four suicide bombers carrying backpacks. All but one of these terrorists were British citizens, influenced by al Qaeda ideology (Stern, 2007). The intention of the suicide bombers had been to detonate their bombs on the underground metro trains, but one of the three terrorists was unable to gain entry to the subway and thus chose to detonate his pack on a double-decker bus at Tavistock Square (Ibid.). In the London terrorist attacks, four suicide bombers detonated one charge each, killing 52 people. Seven people were killed by the blasts at Aldgate, six at Edgware Road, 13 at Tavistock Square, and 26

at Russel Square – in addition to the suicide bombers themselves. More than 700 people were injured.

Mumbai 11 July 2006

On 11 July 2004, in evening rush hour around 18:30, bombs exploded on seven trains in Mumbai (formerly Bombay), the financial center of India. All of the bombs had been placed in compartments of First Class coaches of the suburban Mumbai railroad network. More than 200 people died, and 700 were injured. Police investigations concluded that militant Islamic organizations operating in South Asia were the culprits – specifically the Lashkar-e-Toiba, and the Students Islamic Movement of India. Whereas evidence to support the claim has not been produced, some prominent Indian authorities such as the police have suggested that Pakistan's espionage agency was involved in planning the attacks (Gupta, 2011). The bombs were made of pressure cookers containing a mixture of explosives widely used both in the military and for industrial purposes. The Mumbai 2006 attacks were neither the first nor the last Indian train bombings. For example, train bombs were detonated in Jainpur and Rafiganj in 2002, in Mumbai 2003, in Panipat 2007, in Diphu 2008, and in Gaia 2010.

Trends in Terrorist Modus Operandi

Devices

Improvised Explosive Devices (IEDs) such as those used in the aforementioned attacks are a serious threat to collective traffic, and the components of them are reportedly fairly easy to acquire and assemble.[2] Arms specialists observe that "IED technology is only limited by the ingenuity of the person manufacturing or deploying the devices, so multiple configurations are always possible" (Wilkinson, 2008:140). These improvised bombs, comprised of various explosive materials which may be combined with shrapnel etc., may be located in vehicles or on suicide bombers, either placed or projected (Ibid.). Chemical, biological, radiological and nuclear (CBRN) additions are typically not advocated by terrorists as they are more difficult to obtain. However the risk for CBRN-explosives (CBRN-E) threats remains and prevention and response must be geared to these threats as well (WMD Insights, 2006).

Small groups and "catastrophic" terrorism

Whether instigated by wider terrorist networks or merely inspired by their ideologies, the actual attacks are typically carried out by only a handful of people, and in some cases an individual who may have operated on his or her own initiative. Moreover, all of the five cases documented briefly herein are instances of "catastrophic terrorism," intended to cause as much bloodshed as possible, in contrast to the tradition of many past terrorist movements (e.g. the IRA and ETA), who typically issued warnings prior to an explosion (Carter, Deutch

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[2] The explosive materials used in the Madrid bombs, for example were apparently relatively accessible; the bombs were made of "an explosive used in commercial mining known as Goma-2, and were detonated by the alarms of attached phones that were set to coincide with the times at which the trains would be in-station" (New York Police, 2008:8). According to a special assessment of the Madrid train bombings by the Department of Homeland Security (DHS) in 2004, "[h]ad the second train not been delayed, the bombs would have detonated while the train was in Atocha station" (Ibid.). A bag containing a device composed of 12 kilograms of Goma 2 ECO with a detonator and 136 meters of wire was also reported to be found on the track of a high-speed train on 2 April (Wright, 2004). Goma 2 ECO is a gelatinous, nitroglycol-based explosive used mainly in industrial mining, commonly used in Spain, but also exported. (New York Police, 2008:9).

& Zelikow, 1998). Taken together, the trend of not issuing warnings, the extreme difficulty of discovering small groups or "lone wolves" commencing attacks, and the congested nature of urban rail nodes make the consequences of such attacks severe, although their probability continues to be low. Different groups of Chechen terrorists with similar aims (for example linked to the infamous terrorist group Caucasus Emirate) which have instigated numerous attacks in Russia over the last decade or so are deemed to be among the most organized and well-prepared bombers. Here the "most critical nodes and links" in the subway system were targeted, and the sophistication of terrorist modus operandi is judged as high (Gupta, 2011:27). A norm-critical and gendered perspective is important for gaining understanding of terrorism and other violent acts, whether they are perpetrated by men or women. Gender stereotypes and normative conceptualizations of politically or socially motivated violence may detract from accurate analysis of train bombings and thus the potential to learn from and prevent them. As female suicide bombers are found to attract significantly more media attention than male suicide bombers (Bloom, 2011), the tactical potential of women engaging in terrorism and being engaged in terrorism requires deep and critical analysis.

Hubs, transfer stations and symbolic targets

The objective of terrorists is ultimately to create widespread fear, which they endeavour to achieve by creating the largest possible impact of their actions in terms of causing particularly physical harm, as well as widespread material damage. Empirical evidence from subway and train bombings suggests that bombers will strike at times when stations are congested, such as rush-hour, and also that hubs and transfer stations where the most people are at any given time may be most vulnerable (Gupta, 2011). Symbolic locations also are typically favoured. A network analysis of the London subway attacks in 2005 indicates that the terrorists had studied the system and traffic patterns to carefully assess and plot out three of the five most important stations in central London (Jordán, 2008).

Above and underground impact

Of concern to the METRO project is the difference and consequences of attacks taking place above and underground. For regular trains as well as for subway trains, both types of attacks are possible on many routes. The London attacks took place both underground and above ground (in a bus), in what was apparently an unplanned but fortuitous outcome from a terrorist perspective. Attacks underground potentially imply more damage and death simply because of the higher pressure and blast injuries, with the contained nature of the location also making it more difficult to escape the scene of attack and to receive help. In contrast, attacks above ground have the advantage of being much more visual – i.e. mediated – than underground attacks. Moreover, the clarity of above ground visual footage is arguably more effective than that of dark and smoke-choked sites of underground attacks. Thus, while underground attacks may cause more fear among survivors, above ground attacks seem, ceteris paribus, to have a more fear-inducing effect on a wider audience. Hence, when the bus blew up in London in the 2005 attacks, the rescue services cordoned off the scene of attack as soon as possible, to prevent mediated visualization of the devastation.

Trends in Crisis Preparedness, Mitigation and Response

Strategic Decisions and Learning from Crises

The decision to shut down transport – both above and underground – is a major decision taken in response to terrorist attacks on urban rail systems. It is typically deemed necessary as a first reaction after an attack, with regard to damage and overall vulnerability assessments. In London on July 7, 2005, first the Underground trains and then the buses were taken out of operation. The shutting down of the London Underground was one of the most important strategic decisions made during the crisis, and was in large part a decision based on the lessons from the Madrid train bombings of 2004. In London, approximately 250,000 people in stations throughout the city were evacuated. In addition, measures were taken to prevent motorists from entering the city. The key strategic dilemma is this: managing chaos due to large numbers of people finding it nearly impossible to get home/evacuate (which in London meant that many people walked long distances), or facing further destruction and fatalities in the case that more bombs are positioned for secondary attacks.

It is also clear that authorities tend to want to re-open public transport as soon as possible. In the London case, the Underground was re-opened early in the morning in the following day (after security checks and searches had been conducted), whereas bus transport and commuter and long distance trains resumed traffic on the evening of the day of the attacks.

Another strategic responsibility is the coordination of large number of response and rescue personnel, which tend to involve several hundreds of people. In the London 2004 case, around 1,000 response and rescue workers were directly engaged on the streets – fire fighters, ambulance personnel, and officers from the Metropolitan Police and Transport Police, respectively. In the London case, much of the assistance was circumstantial as medical personnel happened to be nearby attending for example, medical conferences (Fors, 2006). Patients were sent to seven area hospitals (Stern, 2007). Also in the Madrid case, several hundreds of first responders were called in.

In order to learn from subway attacks and improve crisis preparedness and help prevent future attacks, it is integral to examine cases not merely re-constructively from incident onset and response. A comprehensive and comparative organizational perspective, which takes into account the context and circumstances prior to attacks, as well as response and crisis aftermath, is important for identifying and addressing vulnerabilities (c.f. Deverell, 2010:181-187).

Socio-Technical and Network Approaches

Terrorists are innovative in their planning and methods of attack, as the increasing use of IEDs, particularly in conflict regions, has indicated. A number of techniques for detecting and preventing terrorist attacks, as well as for mitigating their destructive impact are employed, as well as under development. Closed-circuit television (CCTV) cameras are for example standard (if not wholly uncontroversial) features of contemporary industrialized urban areas, particularly subway and rail stations and cars, and buses. Human as well as vehicular traffic flows can be monitored and exceptional circumstances identified. Network analysis can complement these preventative measures. Technological advances for detection, for example through the use of sensors,are also the subject of research, although the health and

safety implications of a number of these possibilities are presently insufficiently addressed. Design of urban areas such as platforms and stations and the internal design of subway and train cars can be improved both to heighten preparedness and well as to minimize the impact of explosions.

In terms of design, research following numerous terrorist attacks on buses in Israel has found for example that the higher the backs of bus seats are, the less severe the injuries suffered (Almogy, et al, 2005). Further, barriers and partitions (not glass) generally have shown to be effective for minimizing blast effects.

Whereas neither nuclear "dirty bombs" nor bio-chemical IEDs have to date been utilized by terrorists in subway attacks, there is concern that future threat could come from terrorist innovation in this area. The Scandinavian countries and Norway in particular have expressed increasing concern for example over lack of control over both chemical and nuclear inventories in Northwest Russia for example (Sæther, 2008). Advances in "non-intrusive fissile material identification" are in use and under development for detection of nuclear materials, for example, with the use of acoustic resonance and x-ray technology.

Monitoring sensors for real-time detection of biological agents are also proposed, as is the use of for example GPS and GNSS technologies for, together with meteorological tools, determining spread (Nicogossian, et al, 2011).

A number of technologies exist or are under development for improving the resilience of constructions to strain. Some of these technologies may be relevant for improving train/subway car design. For reinforcing structures, work in nanotechnologies is potentially interesting, although problems with both financing and potential adverse health effects have been identified. Vertically aligned Carbon nanotubes (CNT) and Inorganic fullerenes are examples of such technologies for actually reinforcing structures against extraordinary strain (Tenne, et al, 2008). Some technologies are apparently on the market and are used for protection in the defence and aerospace sectors for example (Ibid.).

Network analysis for predicting plausible attack locations and hence, heightened vulnerability at certain locations is a promising preventive strategy. Evidence suggests for example that "simple indicators such as ranking of infrastructure vulnerability points can perform on par with [considerably more resource-demanding] event-based models in estimating risk and predicting target selection" (Gupta, 2011:20).

Decision support systems[3] and tools are used or under development in a number of contexts for the prevention of for example subway terrorism. Such tools may be helpful, particularly if they have a high degree of flexibility and have been developed with equal attention to socio-organizational and technical parameters. Recognition of inherent limitations of complex systems and cognizance of their vulnerability to accidental or intentional disruption (c.f. Perrow, 1999; 2007) is however, advisable.

For further information read the full report and see the availability in Appendix:

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[3] For example, TRANSEC is a decision support tool used in the United States, primarily however with regard to foreign terrorist threats entering the US via ports (Adler and Fuller, 2009).

- Newlove-Eriksson, L., Literature Review of Cases of Explosions and Threats to Mass Transport Systems, Contribution to METRO Project: Work Package 5: Extraordinary Strain on Constructions, 17 September 2010(revised Final Version: 21 January 2011)CRISMART - Crisis Management Research and Training, Swedish National Defence College

Technical analysis of some explosion incidents in mass-transport systems

Introduction

The seven most serious terroristic attacks on railway systems of the last two decades including explosive devices were summarized and proving the actuality of this danger. This literature study gives technical details about the type, the size and the placing of the explosive devices, describes the damage to the human beings and the structural damage caused by the explosion and points out the problems faced by the first responders. This information was used as benchmarks for the full-scale fire and explosion tests of the METRO-project in autumn 2011 in Sweden.

Method

The information was collected from newspapers, reports of institutions or Internet data, which contradict each other sometimes in numbers. The numbers chosen are the ones that got used by several sources and appeared most trustful. Information collected from newspapers was used with special caution. Only information that was presented in several articles from different newspapers was used in this report. However, even such information may not be reliable since they may stem from a single source, such as a news agency.

Previous incidents

The incidents summarized are some well known terrorist attacks with explosive devices on mass transport railway systems of the last two decades. Following incidents are part of this study: *Paris 25.07.1995, Moscow 06.02.2004, Madrid 11.03.2004, London 07.07.2005, Mumbai 11.07.2006, Moscow 29.03.2010 and Minsk 11.04.2011.*

The majority of the incidents chosen occurred in Underground metro systems. The exceptions are the incidents of Madrid and Mumbai, which happened on ordinary mass transport railway systems. Still they are delivering valuable information about the explosives and the damage to the structure of carriages.

Consequences of the terroristic attacks

Table 7 presents the findings of fatalities caused and information about explosive devices used.

Death and injury comes along in not predictable numbers. Mostly there is only vague information about the size, the type and the placement of the charge. The majority of the attacks were carried out with a single bomb on one train or underground. The attacks in Figure 18 marked with a * were performed with several bombs on the same train.

- *1 three devices exploded on the same train
- *2 four devices exploded on the same train
- *3 two devices exploded on the same train
- *4 seven devices exploded on different trains

In these cases we assume that the explosive devices had about the same catastrophic outcome. To make the numbers comparable the total fatality number was divided by the amount of used explosive devices.

The time line in Figure 19 visualizes the irregularity of the attacks. It can be said that this kind of attacks repeating arbitrarily and can hit any metropolis of the world. The time and places chosen by the terrorists are random. The technical details about the damage to building structures and the underground carriages are rarely mentioned in the reports and articles summarized.

The damage described were shattered windows on the attacked and the adjacent carriage, blown down internal partitions of the train carriage, twisted metalwork, holes in the roof, structural damage or even ripped apart train carriages. Doors could not be opened and debris and luggage were covering the site. The explosions opened up the train walls and metal rods with sharp edges were sticking out and bended in all directions.

Lights inside the tunnel were not existent or not functioning and the communication systems were causing problems.

Incid. No.	Green – No shrapnel used / Red – Shrapnel used	Killed persons	Wounded persons	Ratio wounded /killed	Number of devices	Ratio killed / device	Ratio wounded / device	Size of charges	Ratio killed / 1 kg explosive	Type of explosive
1	Paris 1995	4	62	15,5	1	4,0	62,0	Several kilos		High explosives
2	Moscow 2004	39	129	3,3	1	39,0	129,0	???		???
	Madrid 2004									
3	Atocha	29	115	4,0	3	9,7	38,3		1	
4	Atocha - Tellez	65	165	2,5	4	16,3	41,3	Ca. 10 kg each bomb	1,6	Goma-2 ECO
5	El Pozo	67	56	0,8	2	33,5	28,0		3,4	
6	Santa Eugenia	17	52	3,1	1	17,0	52,0		1,7	
	London 2005									
7	Liverpool Street – Aldgate Station	8	171	21,4	1	8,0	171,0	???		
8	Edgware Road	7	163	23,3	1	7,0	163,0	???		
9	King's Cross – Russell Square	27	340	12,6	1	27,0	340,0	???		Home-made organic peroxide-based device
10	Tavistock Square	14	110	7,9	1	14,0	110,0	???		
11	Mumbai 2006	190	625	3,3	7	4,0	62,0	???		
	Moscow 2010									High explosive hexogen (RDX)

Table 7   Information about fatalities and explosive devices
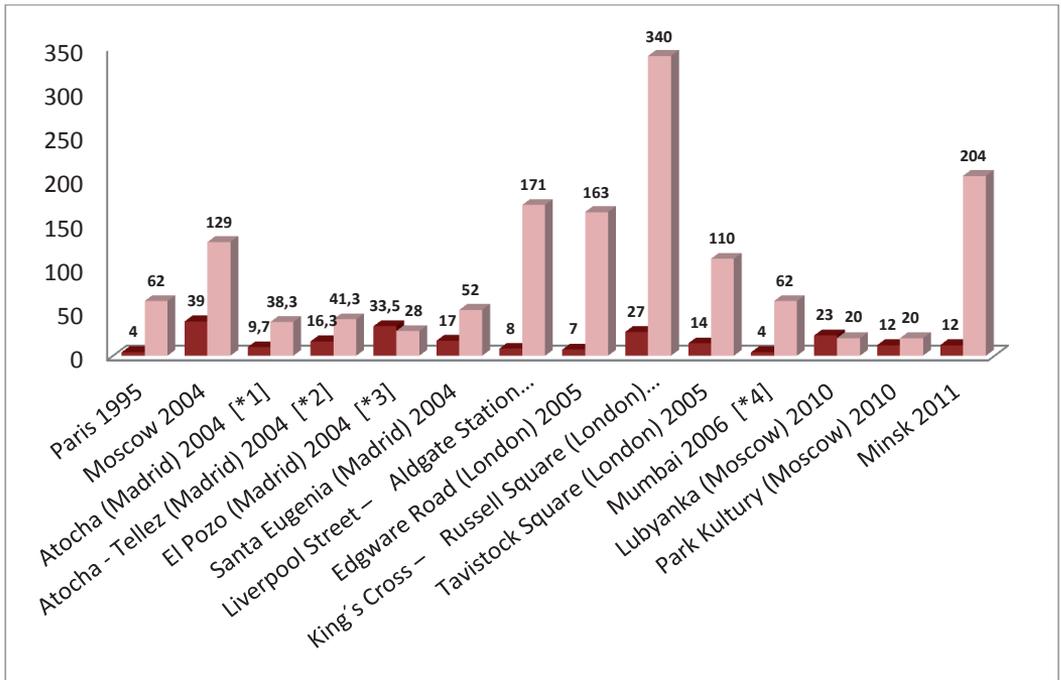
Figure 18   Wounded and dead persons per explosive device
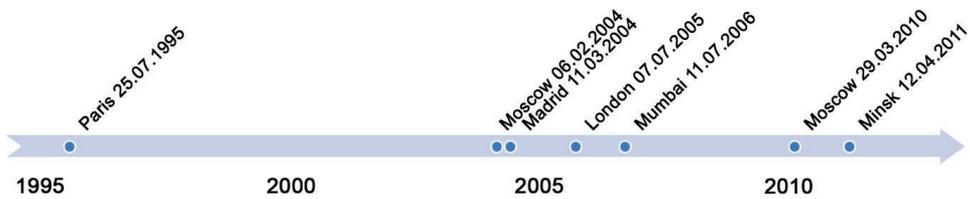
Figure 19   Time line of attacks on mass transport systems

Discussion and Conclusions

The only thing these attacks have in common is the intent to create as much damage and fear as possible. Therefore these attacks were mostly carried out during the rush hour of the cities.

The size and the type of the explosive devices were varying due to the availability for the terrorists. Charges of up to 10 kg were used.

There is a big lack of knowledge about what damage to expect after such devastating deliberate attacks. Knowledge that could be of great help for first responders.

The tunnel systems suffered only minor damages.

Model scale explosion tests

Introduction

A model scale tests of explosions inside a modeled train carriage located in a tunnel were carried out. The scale model tests aimed to verify the numerical simulations of pressure loadings inside and outside the carriage that were made earlier in the project in the same WP.

In the model scale tests, the explosion was assumed to take place at the center of the carriage. It was also assumed that the explosion immediately ripped up a hole in the side walls and ceiling of the carriage with a specific area. The modeled carriage was therefore equipped with a slot near the charge, and in most tests the slot was covered with thin aluminum plates that would simulate the break-up of the side walls and the roof at the time of explosion. The structure of the carriage was otherwise designed as rigid, as well as the inside walls of the tunnel. The slot area, the weight of the explosive charge and number of carriages were varied in order to simulate different scenarios.

Test object

The dimensions of the model carriage were chosen taking the real carriage with model number X1 into account, intended to be used at the full scale test. The dimensions were scaled 1:10 to get a suitable model size to work with. The exterior dimensions of the model carriage were 300 x 300 x 2400 mm (Figure 20 - Figure 21).
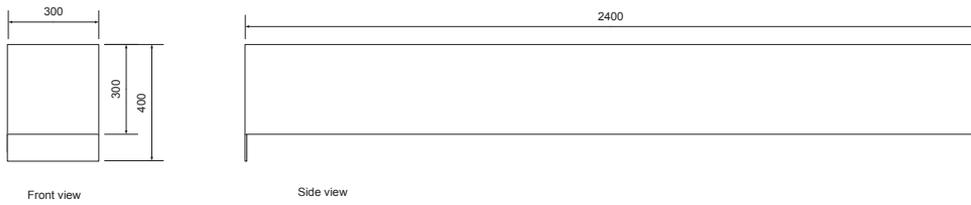
Figure 20   Exterior dimensions of the model carriage (mm)

Figure 21   Exterior view of the model carriage

To simulate the interior of the real carriage, 20 model seats with the dimensions 100 x 100 x 2 mm were made of steel. The seats were then attached in two rows inside the carriage model. The model carriage was equipped with a slot at the center of the carriage with sliding walls and roof sections for varying venting areas. The test started without coverage of the slot but after the first tests the slot was covered with 1 mm thick aluminum sheet to get a more realistic pressure inside the carriage by simulating the resistance in the walls and roof at the time of break-up. A tunnel was built to cover the coach. The inner dimensions of the tunnel were 700 x 700 x 10000 mm, which corresponds to 100 meters in 1:10 scale of the Brunsberg tunnel that would be used for the upcoming full-scale test. Pressure gauges were placed at locations which the numerical calculations showed to be useful for the comparing between the numerical calculations and the model tests (Figure 22-Figure 23).
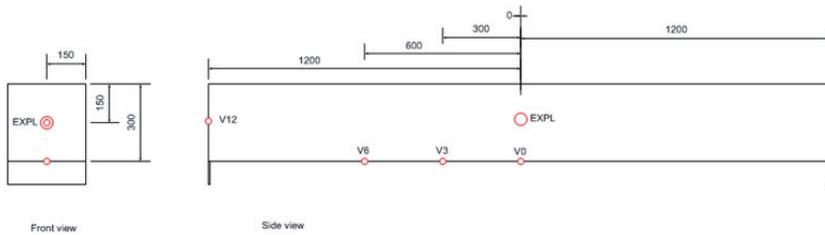
Figure 22   Gauge locations in carriage (mm)
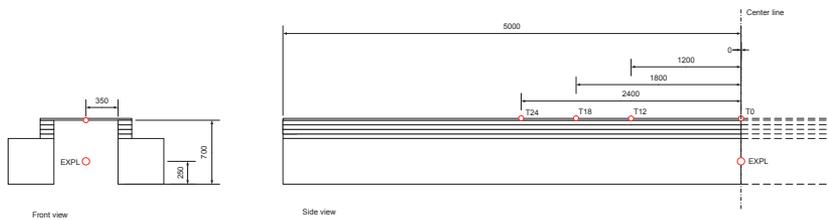
Figure 23   Gauge locations in tunnel (mm)

Altogether 16 shots were made with variations of charge weight, venting area, with or without tunnel and with or without dummy coach. In some tests repeats were made with similar conditions.

Results and comparisons with calculations

- In almost all tests all the gauges gave good legible results. In some cases however there were disturbances in the signal or a zero line shift.
- In repeated tests with similar conditions in most cases the recordings were almost equal. Best agreements of results with similar conditions were reached for the gauges furthest away from the explosion.
- Comparison between calculations and recorded pressure inside the coach show similarities in shape of the pressure curves although there were differences, particularly in impulse density. A suggested explanation to differences in impulse density is energy losses from friction and eddies that occur around the simulated seats that are not accurately modelled in the numerical simulation.
- Even if the model coach was aimed to be rigid some deformations occurred. It was noted that even small alterations of geometry may cause large differences in peak

pressure if the location of the charge is at a point where reflected waves meet and interact

- The technique with covering the slot with 1mm thick aluminium sheet was supposed to get a more realistic pressure inside the carriage by simulating the resistance in the walls and roof at the time of break-up.

In Figure 24, results from an experiment with a 1:10 scale model, a 5 g charge and a 20 dm² vent area covered with loose Aluminum plates are shown, compared with a calculation with 5 kg TNT inside a coach that initially had a 2 m² vent area, widened to 18 m² after 20 ms. Rapid filming made during the experiment showed that the plates moved outwards with a speed of ca 40 m/s.

CALCULATED   **SCALE MODEL TEST**
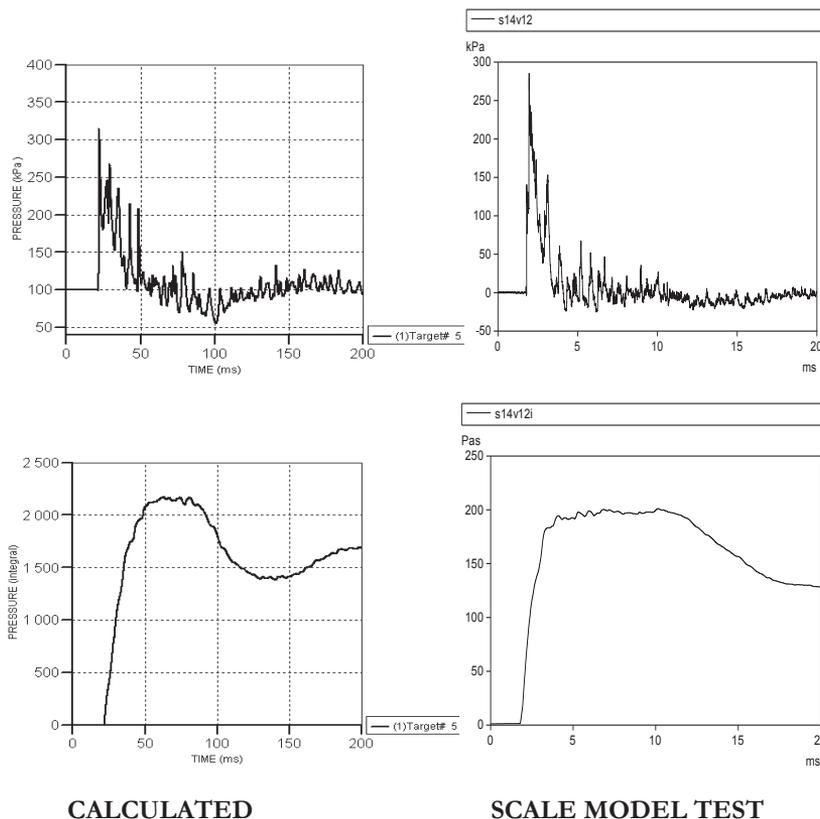
Figure 24   **Comparison between calculated and recorded pressure inside the coach at 12 m distance from a 5 g charge and a 20 dm² vent area covered with loose Al-plate.**

Further information about the tests can be found in the following reports:

- Bryntse, A., Meyer, G. (2011). METRO – Calculated pressure from explosion in train coach - Evaluation of peak pressure and positive impulse density, FOI-RH.--1211—SE.

- Carlberg, T., Berglund, R. (2012). METRO – Scale model tests, FOI-R--3402—SE.

Window response tests

Introduction

These window explosion tests were carried out by FOI in shock tube IV in Märsta, Sweden. The objective was to investigate the breaking of the 5 mm glass pane that is commonly used in the train type X1. Further attention was paid to the hazardousness of the glass fragments for passengers.

Method

In total five windows from a decommissioned commuter train were examined. An explosive device of a certain weight was placed in a certain distance to the glass pane. Some gauges measured the peak pressure of the pressure wave. Variations were made in distance of the charge to the window and the charge weight.

Test set-up

Five windows of a decommissioned commuter train type X1 were collected and used for the experiments. The windows were fixed into a steel frame, which itself was placed centered in the tunnel. The windows had a dimension of 84 x 100 cm and were fixed in a steel frame that was manufactured as similar as possible to a window section of the original commuter train. The fixing for the windows were original parts from the commuter train consisting of a rubber profile that kept the window level with the outside and four aluminum lists along the inside of the carriage wall that were slided into the aluminum frame of the window and screwed to the wall structure to keep the window in place, see Figure 25.
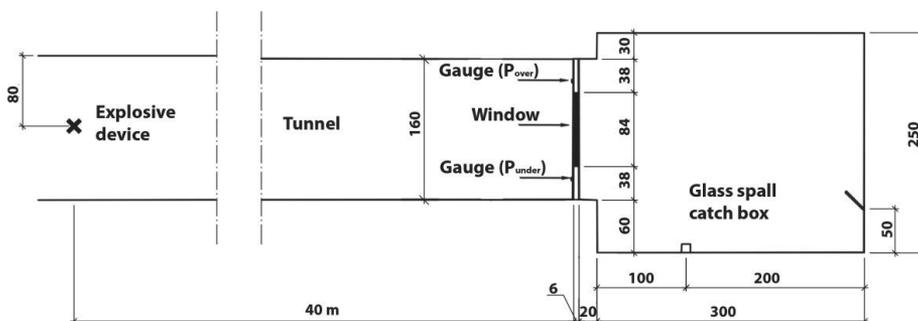
Figure 25   Vertical cross section of the test set-up

Variation were made in the weight of the explosive charge (5, 10, 15, 20, 25, 30, 40, and 80 g) and the distance to the windowpane (20, 40 m). The charge was hung up in the center of the tube so that the pressure wave propagated orthogonal onto the surface of the windowpane. The gauges were placed centered above and below the window so that only reflected pressure was measured.

A white cotton ball was fixed in the middle of the windowpane to get aware of the oscillation during the tests when the window does not break and to estimate the speed of the fragments after breaking.

The glass spall was caught in an adjacent box of 3 m length, 2,3 m width and 2,5 m height that was placed in front of the tube. The sidewall towards the high-speed camera consisted of Plexiglas© and the opposite side showed a white wall with a grid of blue lines. The edge length of each grid square was defined with 0,5 m. That gave the opportunity to calculate the speed of the fragments.

Zones 0 to 4 were created as shown in Figure 26 to be able to categorize the glass spall. The explosive charge used was made of standard Swedish military plastic explosive (sprängdeg m/46), which is composed of 85 % PETN (Penterithrytoltetranitrate) and 15 % mineral oil.
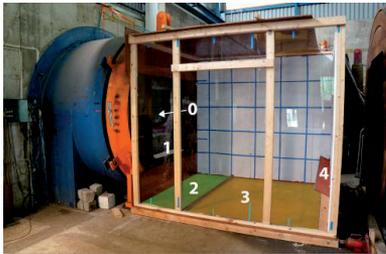
Figure 26   Glass spread zones

The signals were recorded by a Nicolet Vision high-speed transient data acquisition system. It sampled the data at 100 kHz with a resolution of 16 bits, maximum 16 channels. A Photron APX high-speed camera (running at 1000 frames per second) was placed 9 m orthogonal to the tunnel length axis in front of the glass spall catch and got triggered manually.

Results

Observation of glass spread

The spread of the glass spall depends on different parameters like the type of glass, the size of the charge, the shape of the room, obstacles within the travel route and the character of the boundary surfaces.

Except the charge weight all parameter were kept similar during the test serie. With the changing size of the charge the speed of the spall got changed likewise, which led to a significant different picture of glass spread. To be able to categorize the glass spread the room, which catched the glass spall, was divided into 4 different zones, see Figure 26. The glass spall of the 5 broken windows (shot 5, 6, 7, 14 and 15) got weight in by each zone. The following pictures show the plane view after Shot 5 and Shot 7. The arrow indicates the direction of the initial pressure wave propagation.

The glass distribution of shot 5 (25 g) is oriented infront of the Styrofoam wall. The glass got pushed 3 m across the room but had not sufficient energy to renounce from the opposite wall. Most of the spall settled close to the wall in the zones 3 and 4 with a total weight of 8727 g. The window pane unbroken weights about 10,2 kg.

Figure 27   Glass spread Shot 5–25 g

Figure28   Glass spread Shot 7–80 g

After shooting 80 g of explosive the glass spall was found rather equal spread with a slight concentration infront of the tube in zone 2. The glass spall had enough energy to return to zone 2 after rebounding from the opposite wall.

Discussion

The validity of the glass spread within the box is rather limited. It depends utterly on the boundary conditions how much the glass splinters rebound from the objects and therefore where they settle. After a rebound the fragment will lose speed and are therefore not as dangerous for passengers anymore. So it is more of interest to see which way the fragments take initially after the explosion.

To avoid a lot of small glass splinter flying through the air it might be reasonable to use laminated glass. This would stay in one piece and it might be possible to secure it to the frame so that it will not fly loose in the compartment.

Although hardened glass was used the tests show that not all the glass breaks up into small pieces. Some bigger pieces with a weight of up to 65 g were found stuck in the styrodur wall opposite the window.

Calculation of blast load

Introduction

As a part of WP5, numerical simulations of pressure from an explosion inside a modeled train coach located in a tunnel were made (see Bryntse and Meyer 2011). The simulations aimed to estimate the pressure loadings inside and outside the coach in such scenarios and to increase the understanding of the phenomena involved.

For most of the studied cases, the explosion was assumed to take place exactly at the center of the coach. It was also assumed that the explosion immediately ripped up a hole in the side walls and ceiling of the coach with a specific area. The coach was thereby modeled with an opening near the charge whose area was varied for different cases in the study. In some cases this venting area was present already when the simulated explosion was started, and in some cases it was opened some time after the explosion in order to simulate the break-up of the side walls and roof. The structure of the coach was otherwise assumed as rigid and immobile, as well as the inside walls of the tunnel. The vent area, together with some other parameters as tunnel cross section and charge weight, was varied in order to simulate different scenarios.

Calculated pressure curves were compared with recordings from small scale experiments reported in 7.4 at similar measurement points. Calculated values were also compared with damage curves for plausible train glass windows (with values from ESTC (2002) and Forsén (2012)), both for the coach where the explosion took place and for an adjacent coach. Finally, all results were compared to measurements and observations reported by Meyer and Berglund (2011), a full scale test (WE 7) with explosives in a real train coach.

Numerical model

The numerical simulations were made with the hydrocode AUTODYN. The geometrical model is shown in Figure 29 - Figure 30. The coach was modeled as a hollow box with length 24 m and cross-section 3x3 m, located 1 m over the ground plane of the tunnel, which had a cross-section of either 5x5 m or 7x7 m. The geometry is similar to the 1:10 scale models used for the experiments in 7.4. The gauge locations of the numerical model were also similar to the scale model, but with some extra gauges added. The distance between gauges were c/c= 3 m, originating from the detonation point at the centre of the coach.
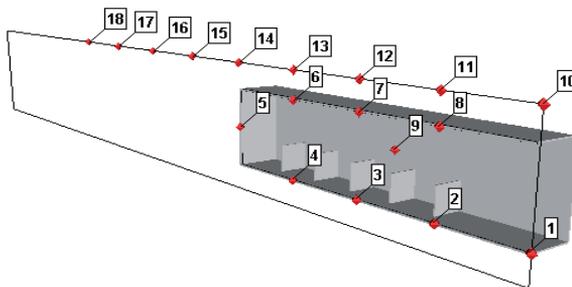
Figure 29　　**Gauge location in coach (nr 1–9), tunnel roof (nr 10–18) for the cases without adjacent "dummy"-coach, all with c/c 3 m**
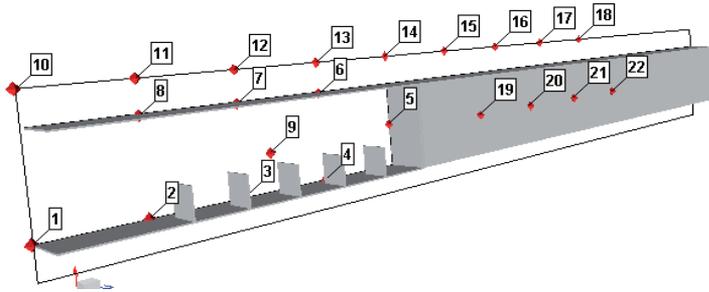
Figure 30   **Cases with adjacent dummy-coach have the same gauge locations but with gauge 19-22 added on the dummy-coach, located at 15, 18, 21 and 24 m respectively**

A total of 48 numerical simulations were made with different combinations of charges, vent areas, tunnel areas, with/without an adjacent dummy coach. The variations in charge weight were 1, 5 and 10 kg TNT. The variation of the vent area in the coach wall and ceiling were 2, 6, 18 and 45 m². The variation in tunnel cross-section area was 5x5 and 7x7 m. A variation with an adjacent coach present or not present was also made.

Sample results and major findings

To illustrate some of the phenomena that occur in the modeled structure with different charge and geometry, two examples (cases) with pressure and impulse curves are shown below Figure 31 - Figure 32.

Example 1: 1 kg TNT with 2m² slot opening and 5x5m tunnel with dummy, Figure 31.
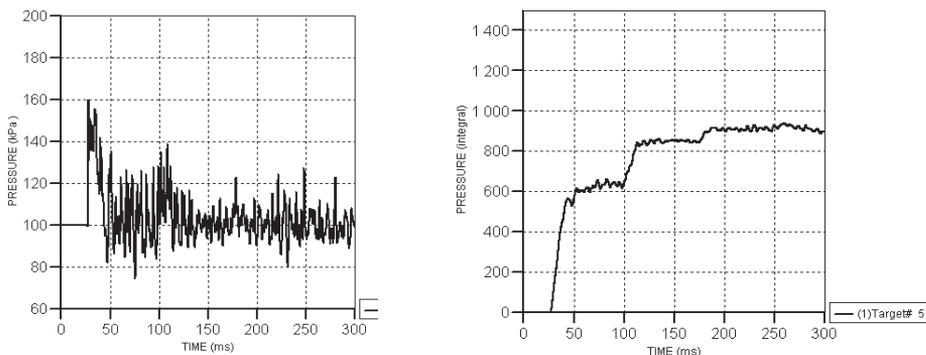
Figure 31   **Inside coach, at the end (12 m from explosion), left: pressure, right: impulse density (Pas). 1 kg TNT with 2m² slot opening and 5x5 m tunnel with dummy coach present.**

When the charge is located at the 2m² –opening, strong reflections from the interior walls occur; shock-waves move back and forth in the coach several times, successively increasing the impulse density in steps with clearly visible plateaus.

Example 2: 10 kg TNT with 45 m² slot opening, 5x5 m tunnel with dummy, Figure 32.
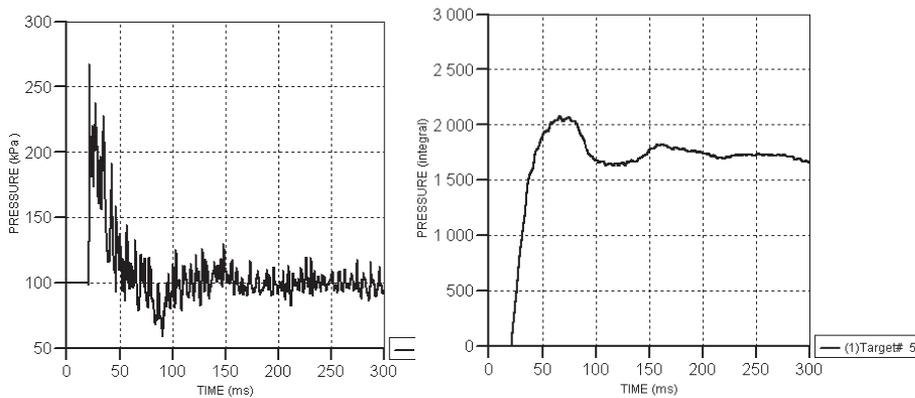
Figure 32 **Inside coach at the end (12 m from explosion) left: pressure, right: impulse density (Pas). 10 kg TNT with 45 m² opening, 5x5 m tunnel with dummy.**

When the charge is located at the 45m² –opening, only weak reflexions from interior walls occur and the reflexions from the coach ends are effectively evacuated through the large opening. The impulse density therefore reaches its final value without plateaus.

Major findings from the calculations were:
- Comparing charge weights 1 kg and 10 kg TNT, both with 2 m² vent area, it can be seen that the impulse density for the higher charge weight is approximately ten-fold for all gauge locations.
- The total impulse density on the dummy coach is almost unaffected when the vent area is changed from 2 m² to 45 m². For structural response analyses it can however be important how fast the impulse loading occur. Therefore, in the evaluation an extra impulse value was read 20-30 ms after wave arrival, usually on the first plateau on the curve, i.e. some time after the first pressure pulse had arrived. This value shows a clear dependence on the vent area
- The peak pressure and impulse density in the tunnel and on the dummy coach was reduced by about 50 % with the larger tunnel area 7x7m, compared to the 5x5 m tunnel.

- The influence on pressure and impulse in the tunnel with the dummy coach present or not is not very significant for the 7x7 m tunnel, however more significant for cases with 5x5 m tunnel.

When comparing calculated values and the results from the full scale test it is important to bear in mind that all conditions were not identical. The geometry and gauge location differed some from the models above; the height inside the coach was only 2.4 m, compared to about 2.9 m in the models. The reflection gauge on the coach end wall was mounted on the driver's cab, about 10.7 m from the center of the coach. The tunnel cross section also differed as it was approximately 6 m wide with a curved roof profile with the maximum height of about 6.5 m; the cross section area was about 35 m². Despite these differences the recorded values and the simulations show similarities.

An overall conclusion is that with numerical simulations and scale model tests, indications to quantify pressure loadings from an explosion in a train coach can be obtained. Adding the results from the performed full scale test, the data could be used as basis for proposals on improved train safety.

Full-scale explosion test in the Brunsberg tunnel

Introduction

The full-scale train explosion test was carried out in Brunsberg tunnel in September 2011 as a part of WP 5 of the METRO project.

The destruction caused by explosive devices has been shown in various terrorist attacks. But it is very difficult to define the size and the type of explosive used by terrorists. The degree of destruction depends on different characteristics, such as size, type and location of the explosive device, the materials and structures used in the construction of the carriage and the possibility of pressure propagation inside the restricted space of a tunnel.

The purpose of this full-scale test was to investigate the effects of explosions in underground mass transport systems and use the results for a correlation with small-scale tests as well as for verification of computer simulations.

In the following an overview of the test set-up and a description of the destruction caused by the explosion are given.

Method

The full-scale test was carried out with accurately determined characteristics and delivered valuable data about the response of materials structures and the pressure wave propagation in such scenarios.

Several pressure gauges were installed inside and outside the carriages to measure the pressure pulses during the time of explosion. After the explosion the destruction was defined by sections and recorded in a table.

Test set-up

Location

The cross-section of the whole tunnel is shaped like a horseshoe and the walls consist of rough rock formation covered in concrete layer with a profile depth of 20 – 30 cm. The height of the cross-section at the location of the experiment is constantly 6,6 m and the width varies between 6,2 m at the east side of the test area and 5,6 m at the west side (see Figure 33). The rail track is arranged partly eccentrically.

Assembly of the full-scale test

The explosive device was made of a common explosive material and was placed on top of a seat cushion next to the aisle as close to the center of wagon A as possible (see Figure 33). That corresponded to 45 cm above the wagon floor and 140 cm above the sleepers. Pressure gauges and cameras were installed inside and outside both wagons to collect data of the pressure wave distribution and to catch pictures of the explosion.
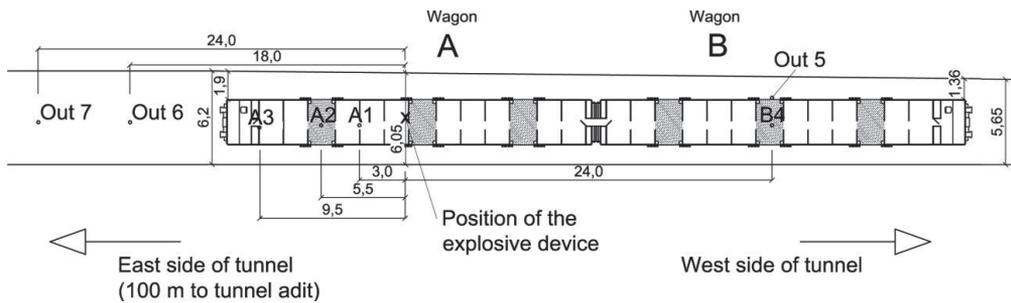
Figure 33   Test set-up

Instrumentation and Equipment

Four gauges were placed inside the wagons, three of them in wagon A (A1, A2 and A3) and one in wagon B (B4). Three further gauges were installed outside the wagons on the sleepers of the track (Out 5, Out 6 and Out 7). All gauges except gauge A3 were set up to measure the side-on pressure. Gauge A3 was installed inside the compartment wall and was set up to measure the reflected pressure.

Results

Train sections

The train is subdivided into sections as described in Figure 34. The explosive device was placed in section 0-A. The subdivision gives a good opportunity to define the location of the

destruction and compare the results of the west (W) and the east side (E) of the detonation. The results from the pressure gages are given in Table 8. The value p is the peak-pressure (kPa), ip represents the first impulse plateau (Pas) and it is the total impulse density (Pas).

Table 8   Results of the gauge measurements

Gauge:	A1	A2	A3	B4	O5	O6	O7
p:	550	200	170*	11	32	32	34
i_p:	940	590	800	780	550	480	450
i_t:	940	1260	1500	780	1100	960	1000

* Pressure peaks occurring after the 170 kPa peak, believed to be electrical disturbances.

Observation of damage

The damage of the train and the interior is strongly dependent on the distance from the charge. The explosion lifted wagon A up and placed the front set of wheels beside the track. Figure 34 categorizes the intensity of destruction with different color zones.
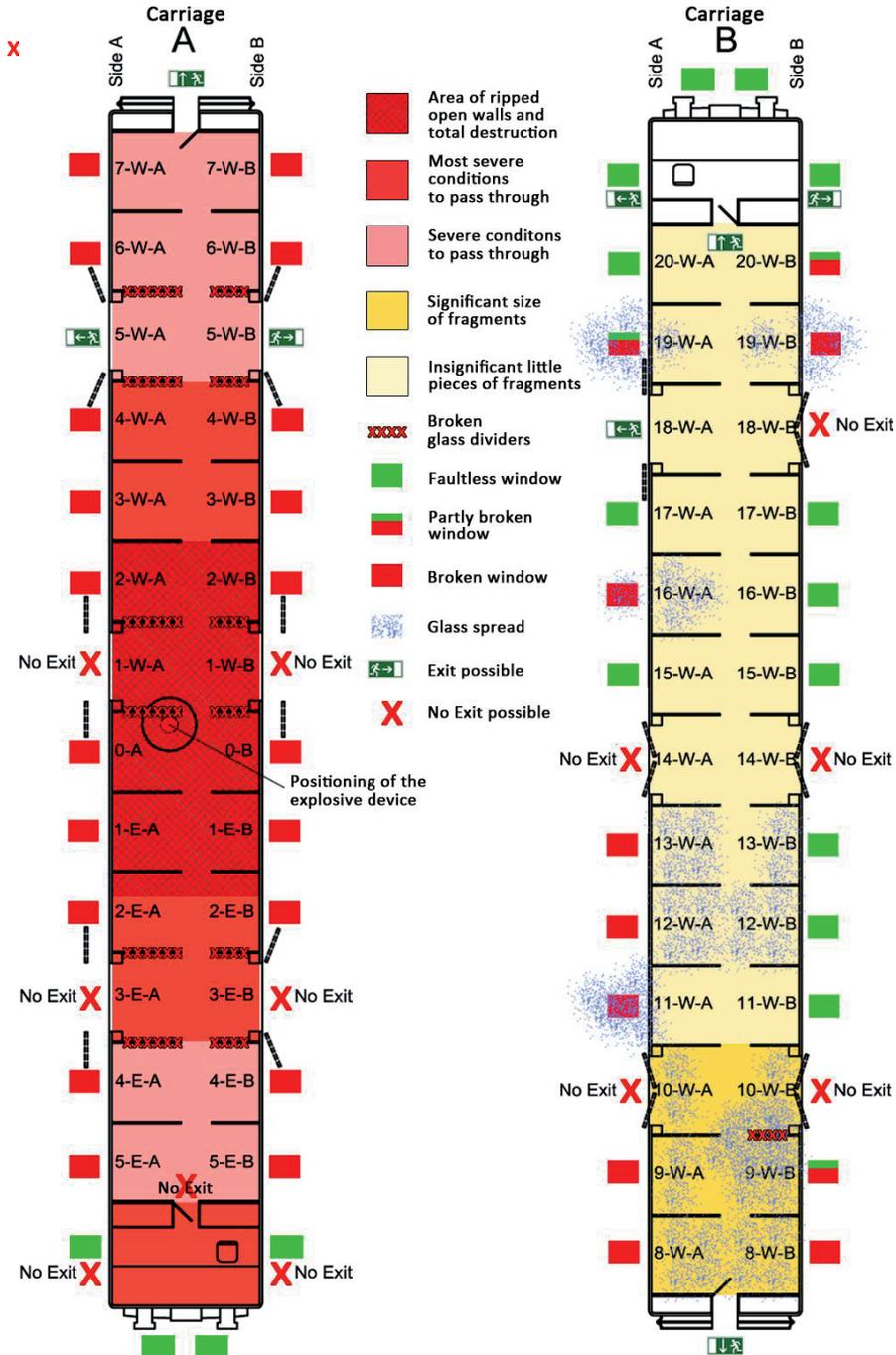
Figure 34   Destruction in Sections

The tunnel structure suffered only minor damage such as parts of the concrete layer were chipping off the rock formations. The rock formations itself did not suffer any visible damage.

Conclusions

The full-scale test has shown some results of high significance regarding safety of evacuation routes for passengers. It also was highly valuable for the education of the participating fire brigades.

- The charge caused tremendous damage to the carriages
- The interior of the affected wagon were destroyed and turned into dangerous shrapnel.
- Some of the wheels of the chassis were blocked by heavy metal debris and one axis even derailed.
- Significant damage was caused to the windows. The glass splinters may become dangerous projectiles.
- The most sensitive part of the adjacent wagon was the exit doors, since they failed in function after the explosion.

The attacks on underground mass transport systems of the recent past are showing the urgency of this topic and the need for further investigations of safer materials and protection of the chassis for rescue and evacuation purposes. Furthermore there is a need to investigate the strength and design of the compartment doors in order to secure a safe and fast escape route, to prevent unnecessary panic and save lives.

Structural response

Introduction

Principles are given for how damage to structures can be calculated (see Forsén 2012). The main focus is put on damage to windows, and damage to people due to broken glass from the windows and from the direct blast effects.

General principles for determination of damage to structures from explosive loading

The response of structures loaded by blast waves from explosions is determined not only by the maximum pressure but of the characteristics of the whole pressure-time history. When evaluating the response, it is common to convert the actual structure, for example a plate or a beam, to an equivalent single- degree- of-freedom system (SDOF system). A SDOF system is a mathematical model where the structure only moves along one axis.

To convert a structure to an equivalent SDOF system, equivalency factors for load, mass and resistance are needed. The determination of these factors is based on equal energy of the

load, of the resistance and the equal kinetic energy for the real system and the SDOF system. An important factor needed for the transformation of a structure, e.g. a plate or a beam, is the shape deflection. In most cases, this parameter has to be assumed.

Once the SDOF system is defined the deflection versus time can be determined by solving the differential equation for the system.

This methodology is frequently presented in the literature and simplified solutions are given for standardized structures, deformed shapes and loadings.

Pressure-Impulse (P-I) diagrams (or iso-damage plots), are often used to illustrate the response of structures to dynamic loads. P-I diagrams present combinations of peak pressure and impulse density causing a certain level of damage. The construction of P-I diagrams can be based on calculations with SDOF idealization, finite element analysis or by other methods such as empirically based.

Damage to windows and humans from glazing fragments

It is common to rate the damage to windows in three levels:

•   Crack threshold or break safe

•   Low Hazard

•   High Hazard

The levels of damage are connected to a standardized test procedure. The window is mounted in the wall of a 3 m deep test cell. If the glass glazing fragments are thrown further than 1 m into the room it is considered low hazard and if the fragments are thrown higher than 0.5 m above floor level onto the opposite wall with the window it is considered high hazard (Figure 35).

Previous work at FOI (Lööf 2006) has concluded that at the threshold of low hazard, the probability of window breakage is 100% and that will cause minor injury to all persons at the inside of the room (within 3 m), 10% severe injury and 1% fatalities. This conclusion is, however, based on use of ordinary window glass, which may break into long, sharp and dangerous splinters, whereas those of hardened window panes are smaller, more "chubby" and prenst a lower hazard.

ESTC (2002) contains a compilation of various windows' resistance to explosion loads. Tables are presented that give the hazard threshold distances for various glazing types (face-on to the detonation) and charge weights. In Figure 36 the evaluated combinations of peak pressure and positive impulse density values are displayed as iso-damage curves together with an estimated curve for a 5 mm thick pane that was tested in a full scale test.
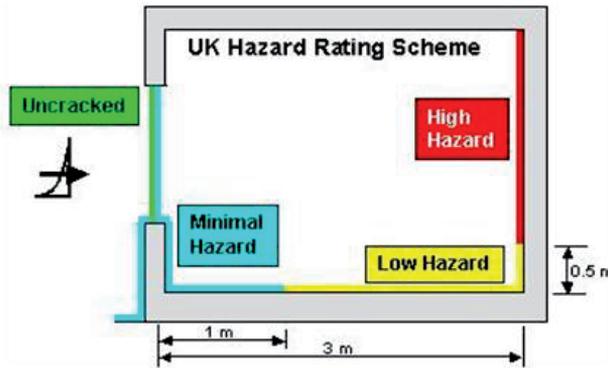
Figure 35   Damage levels according to ''British Glazing Hazard Guide''
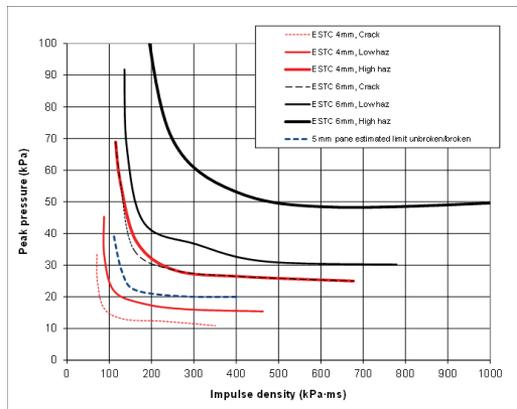
Figure 36   Iso-damage curves for 4 and 6 mm toughened pane with dimensions 1.25 x 0.55 m. Also marked is an estimated Iso-damage curve defining the limit for breakage for a 5 mm pane.

Damage to humans from blast loads

Humans exposed to blast waves may experience damage ranging from temporary or permanent hearing loss, lung damage or lethality. Several references present criteria for damage to humans based on incident (long durative) pressure levels. Values found in Glasstone and Dolan (1977) and ARMY Manual TM 5-1300 (1990) are:

•   35 kPa (5 psi) blast overpressure will cause eardrum rupture in about 1% of subjects

- 310 kPa (45 psi) overpressure will cause eardrum rupture in about 99% of all subjects

- 100 kPa (15 psi) overpressure is reported as the threshold for lung damage

- 240-310 kPa (35-45 psi) overpressure may cause 1% fatalities

- 380-450 kPa (55 to 65 psi) overpressure may cause 99% fatalities.

The pressure levels stated above are incident levels (assuming a free stream situation) while the pressure values calculated are loads against the surfaces of the carriage. Although this difference in assumptions, it is considered that an approximate estimate of human damage may be done by comparing the values above with calculated by (Bryntse and Meyer 2011).

For further information please read the full technical reports and papers and see the availability in Appendix:

- Bryntse, A., Meyer, G. (2011). METRO – Calculated pressure from explosion in train coach - Evaluation of peak pressure and positive impulse density, FOI-RH.--1211—SE.

- Meyer, G., Berglund, R., Lönnermark, A., Kumm, M., (2012). Full-Scale Commuter Train Explosion Test, Mälardalen University SiST 2012:01

- Meyer, G., Berglund, R. (2012). HAZARD OF A BREAKING WINDOW FROM AN UNDERGROUND CARRIAGE DUE TO AN EXPLOSION, Mälardalens University, Mälardalen University SiST 2012:06.

- Meyer, G., Bryntse, A., Janzon, B. (2012). STUDIES OF EXPLOSIONS OCCURRING IN A METRO CARRIAGE IN A TUNNEL, Proceedings from the Fifth International Symposium on Tunnel Safety and Security (ISTSS 2012), New York, USA, 14-16 March, 2012.

- Carlberg, T., Berglund, R. (2012). METRO – Scale model tests, FOI-R--3402—SE.

- Forsén, R. (2012). METRO- Calculated Explosion Structural Damage, FOI-D—0481—SE.

8   WP6 – Fire and rescue operations

Fire and rescue operations in underground mass transport systems easily become a complex and challenging task. Many different parameters, that alone or in combination, will 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. In mass-transport systems many persons can be located close or further away from the scene of the accident. 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 response route often is co-located with the evacuation route for the passengers. Metro tunnels not commonly have cross-ventilation and long distances can be filled with smoke, making both evacuation and the fire and rescue operation difficult. Swedish regulations regarding working environment safety all BA-operations in smoke filled environment should be preceded by a risk assessment. No special advice is given in the regulations regarding BA-operations in tunnels and the safety precautions are usually deciphered conservatively. The limited amount of compressed air available for the BA-rescue team though makes it more or less impossible to bring water filled hoses to fires located more than 250 meters from the tunnel entrance. In these cases more innovative methods for progressing into the tunnel is needed.

In case of a fire in an underground mass transport system, the Incident Commander (IC) most likely needs to make decisions from limited information and the organization often lack of experience from similar accidents. Training and orientation, for all shifts, in systems within the fire and rescue services jurisdiction is usually difficult to arrange and obtain due to the limited time span between the last train at night and the first train in the morning. Performing fire and rescue operations in a complex environment put high demands on the IC and knowledge both about possible risks and the fire and rescue services limitations are needed.

Existing equipment and tactics for fire and rescue operations in underground constructions

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 analysed with respect to the five possible tactical approaches possible to use in case of a fire (Kumm M, Bergqvist A, 2010);

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 airflow 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.

During the METRO project different equipment as a tactic resource have been tested and evaluated. The main groups of equipment are; ventilators, light-lines, trolleys for transportation of equipment and carrying aids for hoses and nozzles. Some of the identified groups of equipment, not tested within the project that would need to be further evaluated are high pressure systems that could increase the moving speed inside the tunnel depending on how long distances from the base unit it can cover and different types of compressed air foam systems. More information about the evaluation of the equipment can be found in:

- Kumm M, Palm A, Technical equipment as tactic resources at fires in mass transport systems, Mälardalen University, Working Report SiST 2012:07.

The fire and rescue services moving speed

Within the METRO-project a number of moving speed tests have been carried out regarding the front BA-rescue team's ability to advance towards the scene of the accident or fire. BA-rescue operations are in Swedish conditions regulated by the Swedish Work Environment Act (1977:1160) with the Provision AFS 2007:7 regulating BA-rescue operations. All BA-rescue operations should be preceded of a risk assessment.

A BA-rescue organization in tunnel environment consists at least of a front BA-rescue team, a BA-safety team, a BA-rescue Commander and a fire fighter in control of the water supply. In cases where there is risk for flash-over the BA-rescue team should bring water for self rescue. The concept with bringing water for self-rescue is commonly called "safe water". The distance between the front BA-rescue team and the BA-safety team is not regulated specifically, but the distance used for BA operations in enclosure fires is 25 meters. The specific value 25 meters correspond to the length of the hoses and a BA-rescue team entering an enclosure fire could easily estimate the distance by feeling the hose connection behind meet the doorstep.

Enclosure fires occur on a daily basis, but large underground fires are fortunately rare. Due to lack of experience, lack of guidelines and lack of secure information about fire development in tunnels and other underground constructions the BA-rescue Commander often use a conservative interpretation of the concept "safe water supply". The Greater Stockholm fire brigade use 75 meters as a standard distance between front and the following safety teams and this has been the Standard Operation Procedure (SOP) during the tests performed in the METRO-project. With normal air supply of compressed air each BA fire fighter carry 2400 liters of air of which 1600 liters are available for the task and 800 liters should be kept for safety reason. The air consumption has earlier as a rough estimation been set to 62 l/min, but has in most tests exceeded that value with approximately 10% when working with filled hoses.
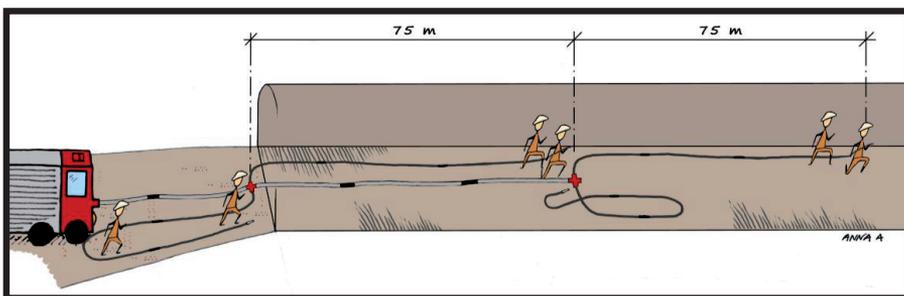
**Figure 37   Test set-up, METRO.
Drawing: Anna Andersson.**

Within the METRO-project the front BA-rescue moving speed and walking speeds have been investigated at eight full-scale occasions;

- Reference tests at Gärdet, Stockholm, day-light, open ground (2010)
- Full SOP-lay out, Stockholm City Line (2010)
- Reference staircase tests, Västerås (2011)
- Complementary tests, inclination, no track, Working tunnel South Link, Stockholm (2011)
- Walking speed tests with helping evacuees, Working tunnel South Link, Stockholm (2011)
- Full-scale fire tests, Brunsberg tunnel, Arvika (2011)
- Full SOP-lay out, Tvärbanan (2011)
- Full SOP-lay out, reference test, Hjulsta metro station, Stockholm (2012)

Figure 38   Hjulsta metro station.
Photo: Gero Meyer.

The fire and rescue operation's front moving speed, including carrying equipment, connection of hoses and advancing forward, is approximately 0,1-0,2 m/s in smoke filled environment, IR-image cameras and filled hoses. The available air limits the amount of time the BA fire fighter can work with moving the front forward and when retreat needs to be made to safely reach the tunnel adit or the point of fresh air before the air supply runs out.

The results from the tests clearly show that a SOP with BA-safety team at 75 meters distance, if filled water hoses are used, limits the action range till 200-250 meters inside the tunnel. In station environment many obstacles can be needed to get past before the tunnel itself is reached. Experiences in brief for station environment is summarized below;

- If carrying equipment the ticket gates can be difficult to pass. It is important that the wider gates are routinely opened in case of fire.
- Some of the gates between the platform and track are too narrow to be able to carry equipment in both hands when passing.
- The switches on the track close to the station can wedge the hose connection and be almost impossible to get loose, especially in dark smoke-filled environments.
- The switches and electrical boxes between the track can significally slow down the walking speed.
- In deep stations the escalators save energy both for fire fighters on the way in as for "used" personnel on the way out.

- Kumm M, Palm A, "The Fire and Rescue Services Moving Speed in Underground Mass Transport Systems", Mälardalen University, Research Report SiST 2012:03.

IR-imaging in tunnels

The use of IR-imaging at normal enclosere fires are common by fire and rescue services worldwide. With higher thermal contrastes the view with IR-imaging can be almost as clear as if the environment would be free from smoke. Tests performed within the project 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 shows very low thermal contrasts. Low thermal contrast, see Figure 40, will make it difficult for the BA-rescue team to evaluate the images from the IR-image camera and estimate borders and directions.

**Figure 39   IR image enclosure fire.
Photo: Christer Johansson.**
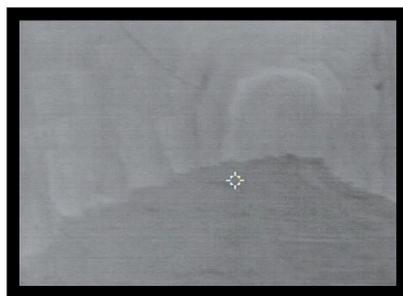
**Figure 40   IR image tunnel, low
thermal contrasts.
Photo: Christer Johansson.**

In opposite, in areas with high thermal contrasts, close to the fire, the distance between the high radiant fire and the tunnel wall can be so small that seeing beyond the fire, in order to find persons downstream the fire can be impossible. In the full scale fire tests in the Brunsberg tunnel in Arvika a "scout-robot" was used to get images close to and from downstream the fire. 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 showed that the sensitivity of the camera automatically switched to "low" when the flames from the fire appeared 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.

Figure 41   **Beside train pointing up-stream fire, high sensitivity mode**

Figure 42   **Beside train pointing up-stream fire, low sensitivity mode**

Figure 43   **Beside train pointing up-stream fire, low sensitivity mode, info Therm Colouring**

Figure 44   **Beside train pointing up-stream fire, low sensitivity mode, info Therm Colouring**

Figure 45   **From train pointing up-stream fire, high sensitivity mode**

Figure 46   **From upstream the fire to-wards train at pulsations, low sensitivity mode, info Therm colouring**

This results from the project 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. The key factors for improved use of IR-imaging in tunnels are appropriate learning tools for the BA-rescue teams for interpretation of images and knowledge of the the IR-image cameras possibilities regarding manual adjustments and settings.

The full-scale fire tests in the Brunsberg tunnel from a fire and rescue perspective

Full-scale fire tests 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. 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 performed by SP in 2003. The Brunsberg tunnel fire tests were performed with the combined focus on both fire and explosion behavior as well as the possibilities for the fire and rescue services. The geometries and tunnel environment have been described earlier in this report in chapter 3.

Objectives of the tests

At real fires no fire and rescue personnel has the time to reflect over the circumstances and environment, except from a safety perspective. The individual experiences are often overshadowed by the team effort. One of the main objectives of the Brunsberg tunnel test, seen from a fire and rescue perspective, was to allow fire and rescue personnel to see, feel and experience a fully developed train fire at close range, in order to later better be able to estimate the capability to extinguish fires during different circumstances. At the Brunsberg tunnel fire and explosion tests four different areas were chosen to analyze more thoroughly, of which the limitations of IR-imaging in tunnels have been discussed in an earlier chapter in this summary report:

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 "scout 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 operations.

The BA-rescue team also had a safety function in the tests in large and could, if needed for test or safety reasons, abort the fire development in the early stages. The later analyzes and assumptions in this report, in respect to the four selected fields, are based on a normally equipped and manned "standard" BA-rescue team in Stockholm Greater Fire Brigade.

Test set up and organization

The test set up regarding water supply, BA-teams and supporting functions, in respect to fire and rescue, was organized as close to real conditions as possible. This was decided for two main reasons; a) the full scale tests were real train fires and could in worst case involve real hazards. If anything would go wrong during the tests there would be no need for improvisation. The personnel would just needs to follow the ordinary Standard Operation Pro-

cedures (SOP), b) from a scientific point of view it was favorable to use the routines and procedures that normally are used in these kinds of operations.

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. The BA-rescue organization consisted one BA-rescue team (2 fire fighters) at the front as close as possible to the train, one BA-safety team 75 meter behind (2 fire fighters), a BA-rescue commander outside the tunnel and an IC responsible for general decisions.
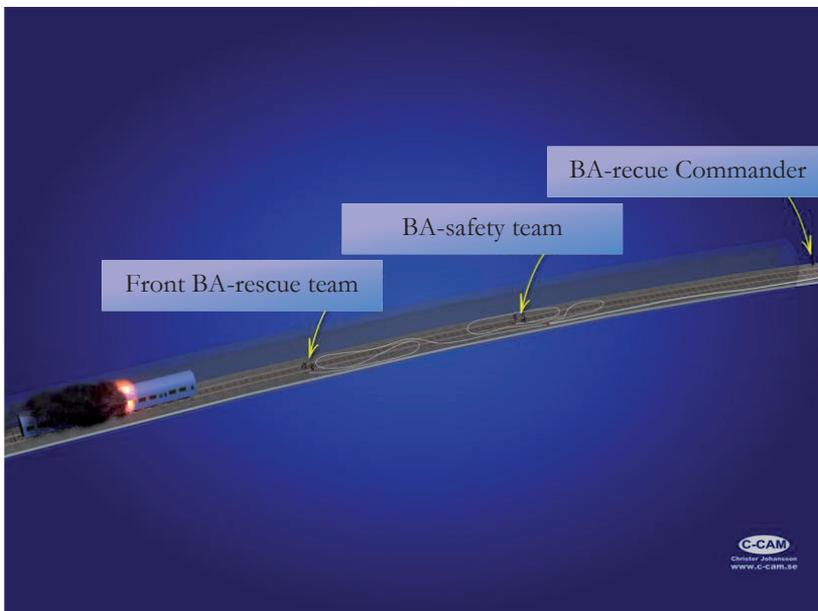
Figure 47   Overview of the BA-rescue organization

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.

During the fire tests additional personnel covered water supply and operation of the mobile fan. 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 each.

Figure 48   BA-fire fighters preparing for the initial fire test

The tests were observed and documented both in respect to the the course of events in the tunnel and the experiences and observations of fire and rescue personnel. The documentation involved video recording both with IR-image cameras and helmet mounted conventional video cameras. Both types of cameras were also mounted on a "scout robot" (ROV) in order to get images from downstream the fire.

Figure 49. The scout robot with the IR-image camera

Figure 50   Mobile high-flow ventilator

Each test was additionally 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 location and observations were later compared to the physical measurements made in the tunnel, for example the temperature, HRR and the heat flux.

Results and observations

The temperatures and HRRs measured in the tunnel are presented in detail earlier in this report and are here only presented as maximum values in order to set the observations dis-

cussed from in a perspective. 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.

Test	Type	Max HRR [MW]	Max temp. (above train) [°C]	Max temp. (downstream) [°C]
1	Ignition	0.5*	-	-
2	Fire	76.7	1073	1081
3	Fire	77.4	1118	980
4	Explosion	No fire	No fire	No fire

Table 9   Temperatures and heat release rates
(* Laboratory value)

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 occured inside the train, 3 minutes in test 2 and 108 minutes in test 3. For short description of tests, see table 9.

Figure 51   Temperature check at ignition test

The fire behavior, apart from the initial time to reach a fully developed fire, has many similarities in maximum values and duration. Both fires declined to the size of a larger car fire in approximately an hour. In cases without further fire spread to adjacent carriages it then would be possible to extinguish with normal resources, which not would be likely at the period with the highest HRRs. 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 assessment.

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. 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.

Figure 52   Pulsations, test 3

Figure 53   Back-layering, test 2

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 were 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. 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 lose 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.

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. The sound-level in the ventilator vicinity could 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.

Figure 54   First carriage, test 4

Figure 55   Obstructed response route after explosion

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. 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.

In case of fire, both in rock hewn tunnels and in tunnels with concrete linings, spalling and parts of the rock itself can become a hazard for the fire and rescue personnel. The full-scale fire tests showed that the concrete lining resisted the fire surprisingly well even if the HRR became unexpectedly high, though could not the exact type of concrete lining be evaluated due to lack of documentation.

Figure 56 Roof behind affected protection. Photo: Anders Högrelius.

Figure 57 Wall close to open carriage door

As it can be seen at the photos above the lining was much more affected close to the open carriage door than in the roof above the train, where the highest temperatures were reached. The results from the full-scale tests indicates that the concrete lining is more sensentive to the thermal shock from the heat flux than higher temperatures, where the heating up of the surface is slower. The tunnel roof was at the tests not affected at all by the short duration of the back-layering. The tunnel itself was onle negliable affected by the last explosion test and most probably the small damages that could be seen was due to the earlier fire tests and only blown down by the blast load. Both the tests and later interviews clearly show that one of the most difficult desiscions that the IC need to make is the judgement of if the tunnel is safe for the fire and rescue personnel due to the spalling of the concrete or falling rocks in the response route.

Conclusions from full-scale tests

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.

The fire and rescue services lack of knowledge of how a fire affects the tunnel itself and when or when not the tunnel is safe from a spalling and falling rock perspective.

9   Discussion

The report compiles the results from the METRO-project. It contains a list of the different reports and papers published by the involved organizations. The different parts – work packages – within the project are described and the findings analyzed. The results from the different parts of the project; design fires, evacuation, integrated fire control, smoke control, extraordinary strain on constructions and fire- and rescue operations are in the following discussed separately.

WP1 – Design fires

The most complicated and expensive part of the project was the performance of the large scale fire and explosion tests in the Brunsberg tunnel. The maximum heat release rates measured from the metro carriage was 77 MW. The maximum ceiling gas temperatures was 1118 °C. These values are high, and should be put into a perspective of the situation and the type of carriages used. Prior to the full scale test, model scale tests and laboratory ignition tests were carried out in order to design the full scale test.

The model scale tests show the importance of the ventilation on the heat release rate. The maximum heat release rate is dependent on the number and positions of the openings. In tests when the fire did not spread due to restricted fuel load, the vent opening had no influence on the heat release rate. In tests with larger openings and when fire spread along the carriage, the heat release rate increased more rapidly. The model scale tests show that the maximum heat release rate increases with the area of the openings since more rapid fire development resulted in more fuels burning simultaneously.

The model scale tests show that the location of the ignition source had limited influence on the fire development. The maximum heat release rate in the test with ignition between two doors was actually somewhat lower than other equivalent tests. A local flashover occurred in the section close to a door opening, but then starts to move to the other side of the carriage until finally the entire carriage were involved in the combustion. The temperature decreases along the distance away from the fire source, thus the parts distant from the initial fire need much more time to reach local flashover. The local flashover was defined as the state that the fire in this zone is fully developed, characteristic as a floor temperature of 600 °C or a floor oxygen concentration of about 0 %. When all doors were open, the spread from left

corner to right corner took about 17 min in real scale. The heat release rate in such cases could be as high as about 20 MW in full scale. This corresponds well to large scale tests with trains when the fire spread along the carriage depending on the openings of the windows or doors.

In the laboratory ignition tests with a 1/3 of a carriage mock-up the first tests the fire never reached a fully developed stage. The fuel arrangement in ignition zone was of great importance in combination with combustible linings. It was concluded that the seats alone did not contain sufficient fuel for the fire to spread within the train, and instead there needed to be luggage in between the seats and enough combustible linings. The vertical flame spread on the walls resulted in a higher radiant heat flux towards neighboring areas and the fuel further away was pre-heated to a higher extent. The combustible linings were found to strongly influence the fire development, even if these only are a small proportion of the entire fire load in the train carriage. When the linings were very sparsely burnt the fire never developed into a flashover. Another aspect regarding the amount of fire load in the train carriage was seen when the fourth test and sixth test were compared. In one test there was no luggage, no petrol ignition, but combustible seats evenly distributed. In another test additional luggage was present and ignited by one liter of petrol, but both tests resulted in a flashover. The main reason was although not the petrol ignition, because in another comparable tests with petrol, but poor vertical fire spread on the HPL boards, no flashover occurred. It was concluded that whether the fire reaches a flashover or not is more dependent on the fire growth in the ignition zone and its neighboring area rather than on the fuel load present further away. This lead to the conclusion that in the full scale tests, the exact arrangement of luggage and ignition source using petrol as in the laboratory tests should be used. The laboratory tests showed that in the cases where the initial fire did not exceed a range of 400 – 600 kW no flashover was observed. If the initial fire grew up to 700 – 900 kW, a flashover was observed. It was also found that the time to reach flashover was highly dependent on the ignition type, i.e. two wood cribs with or without petrol.

The luggage study shows that the carried fire load in mass-transport systems underground can be considerable. The carried fire load in a crowded metro train can be as much as up to approximately 50 % of the fire load of the train itself in this comparison. In the large scale fire tests, this portion was about 20 %. If the luggage is left on trains it can become the factor that makes the fire spread and grow to flash-over. The increased fire load will also prolong the duration of the fire and influence the damage on the construction and the rescue services' possibilities to perform a successful rescue operation. Laboratory fire tests under a hood showed that a pram alone can develops 831 kW. A pram will of course not self-ignite and will constitute a hazard only if it is exposed to some sort of pilot flame like arson or if it is left in the metro coach after evacuation due to fire. The luggage in, under or between different seats is assumed to increase the fire spread significantly. Clearly, it is necessary for train owners to consider this transient load when conducting risks assessments and designing response tactics.

The full scale tests clearly showed that the main reason for the difference in fire growth rate between these tests was due to the involvement of the combustible wall and ceiling lining in the test conducted in the old style X1 carriage. The fire development in test 3 after the fire spread to the passenger compartment was very similar to the one in test 2, when the fire went straight to flashover. The general shape of the HRR curves is almost the same, although the

time for the maximum HRR is very different. The maximum HRR in test 2 was calculated to be 76.7 MW (12.7 min after ignition), while the corresponding value for test 3 was 77.4 MW (117.9 min after ignition), i.e. in both tests the maximum HRR was calculated to be approximately 77 MW. The main reason is that the aluminium sheets melted away when the fire spread from the driver cabin and back into the passenger cabin after over 110 minutes from ignition in test 3. Aluminium has a melting point of 660 °C, and behind the aluminium sheet was the X1 linings, which started to burn. What these tests really show, is that if the combustible linings are protected, or not existing, the fire safety will increase. It should although be pointed out here that the ventilation inside the carriage is also of utmost importance for continuous fire growth to flashover. The estimation of the total energy content in the material in the carriages show it was approximately 64 GJ and 71 GJ, respectively.

The gas temperature inside the carriage reached approximately 1000 °C in both tests and although the large difference in fire development, as discussed above, the temperature development for the parts when the entire carriage gets involved in the fire are similar to each other. In the tunnel ceiling, the maximum temperature was approximately 1100 °C both tests. However, the maximum temperature was somewhat higher in test 3: approximately 1118 °C measured above the centre of the carriage, while the maximum temperature in test 2 was approximately 1080 °C, measured at the position +10m (10 m downstream the centre of the carriage). A method presented by Li and Ingason (2012) was used to calculate the ceiling gas temperatures in the tunnel. The method was found to work very well for the conditions tested. The method considers the ceiling height, height to the fuel load, the heat release rate and the ventilation conditions.

A study of the correlations between three different scales (1:10, 1:3 and 1:1) was carried out. It shows a good correspondence between heat release rates, gas temperatures and gas concentrations. This is very encouraging as the technique gives opportunities to study different fire phenomenon.

The large scale fire tests resulted in peak heat release rates of 77 MW after 13 minutes, and tests presented by Hadjisophocleous et al. (2012) show values of 53 MW after 9 minutes. With this fact as a base, a value of 60 MW was found to be reasonable choice as a "worst case" on a platform (carriage doors open). This value was used in the work in WP4 – Smoke control. These fires developed rather fast, whereas the more slow growing fires varies between 13 MW and 32 MW, with a peak after more than 18 minutes, see Table 1. Further, the model scale tests (1:3) showed a peak heat release rate of 20 MW, after 17 minutes. The fire spread slowly along the length of the carriage, even if the doors were open. A reasonable choice to work with in tunnels is 20 MW. A medium fire growth rate is reasonable for this type of carriage fires. For the 60 MW, an ultra-fast or fast is better representing the fire growth rate. These values are proposed as design fires in WP1.

WP2 – Evacuation

A literature study, questionnaire, small and medium scale tests were carried out. It was confirmed that one of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate an evacuation. The results also show that the train exit configuration will have some impact on the flow rate of people in an evac-

uation situation. However, the population density in the tunnel, i.e., the crowdedness in the tunnel, seems to be one of the main determining factors for the flow rate of people in the train exit.

Novel data that are particularly valuable in evacuation analyses of underground transportation systems was generated in WP2. This data fills a great gap of knowledge in the field of tunnel evacuation. The results show that the people move with an average of 0.9 meters per second in a smoke filled environment with an average visibility of 1.5-3.5 meters.

A simple audible way-finding installation at the emergency exit, i.e., a loudspeaker, was found to perform particularly well in terms of attracting people to the door in smoke filled tunnels. The study showed that other installations consisting of combinations of lights were not as effective, and some designs even discouraged people from using exits. One system that performed particularly poorly was perceived as a train, gearshifts, or other track related installations. These are aspects that need to be considered in future infrastructure design.

WP3 – Integrated Fire Control

As the work within WP 3 Integrated Fire Control substantially depend on the results from the research in other work packages the most important work in WP 3 has not yet begun. SL has due to the re-organization great challenges to encourage and motivate the new entrepreneurs to use the knowledge from the project and implement the new methods. The governance of high standard fire safety is not only measured in regulations, pounds and pennies but in sharing knowledge and making safer metro systems a joint mission. As the work not yet can be evaluated it will not be further discussed in this chapter.

WP4 – Smoke control

The results of the work carried out on smoke control show that the choice of criteria for control of the spread of smoke and temperatures is decisive in determining the capacity of a smoke control system. Two smoke control systems have been simulated, a pressurizing supply air system and mechanical exhaust ventilation system with and without platform screen doors. The results show that both the pressurizing supply air system and the mechanical exhaust system provide effective smoke control.

Two fires were simulated, a 20 MW fire and a 60 MW fire. These fires were chosen in discussion with WP1. The required performance criterion was to keep the escalator bottom lobby free of smoke. To do so with a pressurizing supply air system requires an air flow of 40 m^3/s for a 20 MW fire, and 80 m^3/s for a 60 MW fire. A mechanical exhaust air system requires considerably higher air flows: 100 m^3/s to deal with the 20 MW fire, and 180 m^3/s for the 60 MW fire.

Both systems have advantages and disadvantages. The advantages of a positive-pressure supply air system are a relatively simple installation and a lower requisite flow capacity of the fans. The disadvantage is that the smoke not dispelled, but can spread to the other platform of the station. The advantages of a mechanical exhaust system are that the hot smoke is re-

moved, and that the spread of smoke is restricted to the platform directly exposed to the fire. Disadvantages include the need for a duct system (which requires space) and considerably higher fan capacities.

WP5 – Extraordinary Strain on Constructions

The METRO project focus on explosion and fire as two separate events, but a combination of these two hazards can potentially lead to even worse consequences. If a small explosive is combined with fire accelerant there is a significant risk of an extremely severe disaster in underground transportation systems. The reason for this is that the explosion might destroy much of the fire protection features, e.g., removes the fire retardant wool fabric from seats thereby exposing the foam material to the fire. For the purpose of the WP 5 study, it was decided not to combine these two hazards. The alternative would have been to put accelerates together with the explosives, but the post-documentation would have been difficult.

Antagonistic violence or terrorism in the form of explosions (or accidental explosions) can lead to serious consequences for travelers in metro transportation systems. A literature review of past events showed among others, as discussed in chapters 7.1 and 7.2, that the only thing these attacks have in common is the intent to create as much damage and fear as possible. Therefore these attacks were mostly carried out during the rush hour of the cities. The size and the type of the explosive devices were varying due to the availability for the terrorists but charges of up to 10 kg were used. There is a lack of knowledge about what damage to expect after such devastating deliberate attacks, but such knowledge is of great help for first responders. In all the documented cases the tunnel systems themselves suffered only minor damages.

The efforts to analyses the blast load from explosions on a train carriage located in a tunnel comprised both tests at small scale and numerical simulation work. An overall conclusion is that with numerical simulations and scale model tests, indications to quantify pressure loadings from an explosion in a train coach can be obtained. Three work elements performed covered the area of response and consequences of structures and humans exposed to explosions in underground train carriages. An analytical method to determine the damage to explosively loaded train windows showed good resemblance with experiments.

A performed full scale test with a train inside a tunnel, where a small bomb in a bag was located on a seat, gave valuable data to compare with calculations, small scale tests and component tests with windows. It was also an opportunity for first responders to get a realistic picture of the environment after this type of explosion. It was obvious that the interior of the coach became heavily damaged. This is expected to have a major impact on the type and amount of damage to people. It is also expected to have a major impact in hindering self-evacuation and on the ability of first responders to help evacuate people in the carriage. The direct pressure effects alone against people inside the coach from a small charge are not expected to be critical for the level of casualties, but possibly psychological shock, temporary or permanent hearing loss (which may be accompanied by dizziness and balance disturbances) may affect the speed and ability of evacuation.

Damage to humans by glazing fragments outside the carriage (for example on a platform) can be expected, and also in an adjacent carriage such damage cannot be excluded. It is considered to be a quite serious complication that virtually all doors in both the carriage exposed to the explosion and those of the adjacent carriage(s) were jammed shut by the pressure of the explosion, and the doors could not be opened without tools. This will seriously aggravate evacuation, which must then occur through the destroyed windows.

Experiments and simulations have provided increased confidence in ability to simulate this type of scenarios to determine the explosion pressure inside and outside the car and to be able to study variations of conditions such as carriage geometry and window designs. Fast relief of pressure through a lightweight part of the coach, which will open up at an explosion, will reduce the pressure in the carriage but it is very doubtful whether this would be a viable approach to significantly reduce the risks of this kind of scenario. However the design of the interior may affect the level of casualties, such as the presence of intermediate glass-panes that will fracture and spread splinters.

WP6 – Fire and Rescue Operations

A rescue operation includes a rapid course of events in which human life and health often is at stake. The rescue personnel must have adequate training and equipment to work efficiently and quite often, it is required that the IC must make quick decisions based on limited information during a short period of time. A rescue operation in a train tunnel adds challenges to the rescue personnel who are set to perform it. The factors that are relatively foreseeable at the surface, suddenly becomes complicated and extensive in an underground environment.

The full-scale fire tests clearly shows that under certain circumstances a fire in an older train in a tunnel could peak at values that would make an fire and rescue operation impossible in less than five minutes. In case of fire spread between carriages the fire can burn for several hours and exhaust the organization and put both decisions and logistics at test. When in the fire development the fire and rescue services reach the train, i.e. the response time in combination with the fire development in the early stages, is the single most important factor when it becomes to fighting tunnel fires.

Some of the key factors that influence the outcome of a fire and rescue operation in mass transport systems are:

The large number of people

The rail network is an important part of our cities mass transport system. On each train there may be thousands of passengers that in the event of a fire may need to evacuate the train and platforms in an orderly manner. Potentially, there may be hundreds of people that to different degrees may need to be evacuated by rescue personnel. Normally, the evacuation from underground facilities is based on self-evacuation with the train stopped to halt at a station. But, one will never get away from the fact that older and disabled people always will need help with their evacuation in the event of a fire. Even if the tunnel operators standard procedures in case of fire is to proceed to the nearest station, both national incidents and international accidents show that this not always is possible. In case of fire both evacuation and a fire and rescue operation is more favourable if allowed at the platform instead of inside the tunnel. A larger fire inside the tunnel could cause severe injuries or casualties.

The fire load and train interior

Although modern trains have a limited amount of combustible materials in the interior, the carried fire load could prolong the duration of the fire. The carried fire load could be the factor that makes the fire develop and either it stays on-board the train and contribute to the fire or is carried off the train and risk to obstruct the evacuation or fire and rescue operation it is a factor that needs to be considered.

Geometry and surface material in tunnel

The tunnel geometry provides conditions for the smoke to very quickly spread in either two directions. The hot smoke stacks found in the tunnel roof can easily ignite combustible materials at long distances from where the fire initially started. In most tunnels the surface material is made of concrete or rock. These types of materials have a tendency to spall when they are exposed to sufficiently high temperatures. This can cause the structures to fail and it imposes an imminent risk to the people that are near heat exposed surfaces.

Fire and rescue operation logistics

Long response route, smoke spread and large fire loads, leads to the need of extensive use of BA´s and other fire fighting equipment. In a smoke-filled tunnel the fire fighters often need to transport both themselves and their equipment considerable distances before they reach the location of the fire. In worst case this could lead to the personnel running out of breathing air and thus action time before they even reach the fire. From this perspective it is therefore important that the correct response route can be selected initially. This can only be done if accurate and accessible information is provided to the responding fire brigade.

Explosions in mass transport systems

In the event of an explosion in underground mass transport systems the fire and rescue services need cutting and heavy rescue equipment that not necessarily are kept at all fire and rescue units. The personnel could have to spend valuable time to at all reach the passengers in need and some of the response routes could be totally blocked and make the chosen direction impossible. Sharp edges and uncertainties regarding if the carriage is safe from a construction perspective could slow the fire and rescue operation.

The response route

The risks and difficulties for the fire and rescue services increase with the length of the tunnel. In mass transport systems many barriers and potential obstacles needs to be forced

before even reaching the tunnel. The ticket gates, the escalators, the platform edge at the tunnel entrance and the switches close to the platform are the ones that most affect the response time. The passing time for ticket gates and escalators can be shortened by well communicated and considered contingency planning, smart design and well planned exercises.

The limitations in capacity of the fire and rescues services involved in tunnel fires depend on some key factors. One of the most important is the overall response time. For many fire and rescue services this could be up to one hour or even more dependent on the complexity of the tunnel and the traveling distance to the tunnel. The full-scale tests in Brunsberg tunnel clearly showed that the difference in fire development between test nr 2 and nr 3 (over 1 hour) would have been crucial for the outcome of the fire in a real life situation.

Another key factor is the action time for the fire fighters well in place at the scene of the fire. Here stands the physical strain on the personnel and the air consumption out as limiting factors for long endurance in these kinds of fires.

It should be noted that the normal action time for a Swedish firefighter with standard BA equipment normally is between 20-30 minutes. After that time additional air or replacement is needed. This fact also points out the need of organizational and logistical capacity to support a large rescue operation over time.

10   Conclusions

Fires in trains or individual carriages have been found to be larger than earlier expected (77 MW in the full scale tests). If the carriage doors are open or not were found to have a large significance for the fire development as well as the type of interior wall and ceiling material in the carriage. The "luggage factor" is not commonly used when defining the fire load but the project show it should. It was shown that the luggage play an important role in the initial stages of the fire development.

Based on the large scale experiments carried out in the project and by other researches it is proposed that a fast fire growth rate with a peak of 60 MW should be used for design of the fire ventilation systems at a metro station. This represents a worst case scenario with arson involved and all doors open in the burning carriage. If the fire resistance of the interior lining material, seats and windows are proven to be of high quality the designer can consider to use a lower value, such as 20 MW. The definition of high quality are left to regulators to define. Another design fire should also be used in the design of the tunnel fire safety with all doors closed.

A literature survey and calculsations shows that this design value should be a 20 MW maxiumum with a medium fire grows rate. The ceiling temperatures for the design of the construction both in the tunnel and the station can be calculated by a model proposed by Li and Ingason (2012) which relates heat release rate, ceiling height and ventilation. As an alternative to that method a time temperature curve using the European TSD curve in 2008/57/EG is valid in most cases in railway tunnels.

Based on the egress literature review, it is concluded that human behavior in fire is complex and that it sometimes can seem irrational to a person studying the behavior in retrospect. But instead of using the term 'panic' to describe the human behavior in, and the outcome of, an accident, the adoption of a clear theoretical framework will aid the understanding of the behavior. It is recommended that four main theories are used, namely (1) the behavior sequence model, (2) the affiliative model, (3) social influence and (4) the theory of affordances. Further, the egress study confirm that one of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate an evacuation. It was found that the participants in the tests performed moved with an average of 0.9 meters per second in a smoke filled environment with an average visibility of 1.5–3.5 meters. This visibility level can be easily obtained in metro stations or tunnels with the design fires

proposed. Further, a way-finding installation at the emergency exit, which consisted of a loudspeaker, was found to perform particularly well in terms of attracting people to the door. Also, identification of key factors regarding the difficulties for persons with disabilities to evacuate from trains in tunnels was presented.

Two smoke control systems were simulated for a single exit metro station. The systems consisted of a pressurising supply air system and mechanical exhaust ventilation system with and without platform screen doors. The results show that both the pressurizing supply air system and the mechanical exhaust air system provide effective fire gas control for one exit metro station. The advantages of a positive-pressure supply air system are a relatively simple installation and a lower requisite flow capacity of the fans. The advantages of a mechanical exhaust system are that the hot smoke is removed, and that the spread of smoke is restricted to the platform directly exposed to the fire. The significance of the platform screen doors was shown to be important. For example could well designed dividing sections between train and platform help against smoke spread between the platforms.

Experiments and simulations have provided increased confidence in ability to simulate this type of scenarios to determine the explosion pressure inside and outside a carriage and to be able to study variations of conditions such as carriage geometry and window designs. The results show that a large portion of underground rail transportation systems can be affected by relatively simple but coordinated terrorist fire attacks. The explosion test performed show that an explosion with a relatively minor charge can significantly change the conditions for both evacuees and the rescue service. In the test, a small charge was detonated inside a carriage inside a tunnel. This explosion drastically changed the condition in the carriage of origin by blowing over seats, luggage and partitions, and conditions in adjacent carriage were also heavily affected. The test showed that, although adjacent carriage looked relatively unaffected, some doors of the train were jammed and not possible to open even using the emergency opening procedure. These results show that the conditions for evacuation and rescue operations can change dramatically as a result of a relatively minor explosion.

Single exit stations typically are designed with active systems, e.g., smoke management systems, based on the assumption that there is only one fire. Coordinated attacks in single exit stations might involve the utilization of these systems to inflict maximum harm. Another example of coordinated attacks is a small fire that directs many people to one area of the underground rail transportation system where a more severe fire is set, e.g., using the existing designs to create an entrapment situation.

The full-scale moving speed tests that have been carried out within WP 6 shows the limitations if a burning train comes to a halt inside the tunnel instead of at the platform, that is the standard routines for metro operators world wide. To be able to perform a successfull fire and rescue operation inside a tunnel in a metro system some key factors have been identified; the easy access through ticket gates and escalators, the possibilities to proceed the first distance in smoke free environment, i.e. for example the use of platform doors and the possibilities to transport equipment and if necessary injured persons back on trolleys or other vehicles along the track. Another limiting factor is the available compressed air for the BA-rescue teams. Using oxygen systems would prolong the action time, but instead take away the possibilities to, if needed, use rescue air for collegues and evacuees. Experiences from real life fires

where oxygen systems have been used also have shown problems with over-heating, but the two systems should be more thoroughly compared and evaluated.

For Swedish national conditions new guidance for risk assessment prior BA-rescue operations in tunnels should be developed. The risk for flash-over in tunnels with an longitudional air flow is minimal, even if local flash-overs of course can occur in trains and carriages. If the water hose not at all times is needed for self protection, more effective systems for way guidance to safe and smoke free areas can be used, for example light lines. In complex tunnel systems, close to stations, it is important to have a safe retreat, but effort and air can be saved if some of the transportation can be performed with lighter equipment.

The use of IR-imaging in tunnels needs to be further evaluated, as interpreting the images is difficult for a un-excersised eye. New IR-image cameras have many possibilities with special adjustments, but in operational use it is difficult to adapt. There is a need for adjusted simple settings that can be used in tunnel environments in combination with further education for first responders in intrpreting IR-images.

A few studies have been performed by the physical limitations for fire fighters, but they are mainly used in the recriuting processes prior employment. More physical limits for operational fire and rescue situations are needed to better judge the fire and rescue services capacity and endurance for larger fires.

11 Recommendations

- A design fire of 60 MW (worst case arson scenario) with a fast fire growth rate is proposed for the design of the ventilation system at metro stations. If the fire resistance of the interior lining material, seats and windows are proven to be of high quality the designer can consider to use a lower value, such as 20 MW. The definition of high quality are left to regulators to define. No effects of fixed firefighting systems are assumed.

- A design fire of 20 MW with a medium fire growth rate is proposed for a tunnel system connected to a metro station.

- In a performance based design, a method presented by Li and Ingason (2012) is recommended. As an alternative to that method in a prescriptive fashion, a time temperature curve using the European TSD curve in 2008/57/EG is recommended.

- A walking speed of 0.9 m/s for a visibility of 1.5-3.5 m is proposed as an average value. Design values below 0.9 m/s should hence be chosen for this visibility range.

- A positive-pressure supply air system or a mechanical exhaust system is recommended as a smoke control solution for single exit metro stations.

- Platform screen doors are recommended in one- tube underground stations as a part of a technical fire safety solution.

- High fire resistance of interior lining materials and windows in passenger cabin as well as driver's cabin are recommended.

- It is important for first responders to be aware of the extreme environment after an explosion in a underground train carriage, and to be trained and properly equipped for such situations.

- The problem with doors that were jammed shut after explosion should be further investigated and solved.

- It should be further investigated how the interior design of train coaches can be improved to reduce casualties in case of an explosion.
- New guidance for risk assessment prior BA-rescue operations in tunnels should be developed.

- In metro tunnel systems it is important that station personnel have routines to easen access for the fire and rescue services, for example through ticket gates, in case of fire.

- Stations, or the fire and rescue services, should be equipped with trolleys or similar vehicles to transport equipment or injured persons in case of fires or explosions inside the tunnel.

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

- 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 and needs to be further evaluated.

12   Future work

The METRO project revealed a number of potential problems in underground rail transportation system that needs to be investigated in future research projects. Some of the most important topics or issues discovered in the METRO project are:

- Coordinated terrorist fire attacks
- Changing conditions due to explosions
- Combination of explosives and fire accelerants

Coordinated terrorist fire attacks

Coordinated attacks are seen as a severe hazard in underground rail transportation systems and something that needs to be addressed in future research projects. Coordinated attacks typically require knowledge about the underground transportation system, e.g., the layout and system design, but the fire sources are simple and easily accessible. Two garbage bags filled with gasoline might be enough to take out big sections of an underground rail transportation system. Also, existing underground stations and tunnels are often designed based on the assumption that there is only one fire or hazard. The focus should be on answering the following question; How can underground stations and tunnels be designed to reduce the consequences of coordinated attacks? Multiple solutions to the problem might be possible, and examples include organizational changes, dynamic evacuation systems, dynamic smoke management systems, fire extinguishing systems, etc.

Changing conditions due to explosions

The antagonistic studies show that an explosion with a relatively minor charge can significantly change the conditions for both evacuees and the rescue service. In the test, a small charge was detonated inside a railway car inside a tunnel. The results put a focus on a problem that needs to be addressed in the future. It is therefore important to study how conditions change and if/how evacuees and rescue service personnel can handle this situation.

Combination of explosives and fire accelerants

If a small explosive is combined with fire accelerant there is a significant risk of an extremely severe disaster in underground transportation systems. The reason for this is that the explosion might destroy much of the fire protection features, e.g., removes the fire retardant wool fabric from seats thereby exposing the foam material to the fire. These types of phenomena have not been studied in detail and should therefore be included in future research. The research should focus on examining what types of fires that can result from a combination of a small explosive and fire accelerant and how the consequences of such an attack can be mitigated.

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Appendix – List of publications in the METRO project

The following publications are available on www.metroproject.se/publications :

Ingason, H., Kumm, M., Nilsson, D., and Lönnermark, A., et al. (2012). ***The Metro Project. Final Report,*** **Research Report SiST 2012:08.**

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Fridolf, K., Nilsson, D., & Frantzich, H. (2011). Fire evacuation in underground transportation systems: A review of accidents and empirical research. Fire Technology. doi:10.1007/s10694-011-0217-x.

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Fridolf, K. (2013). Evacuation experiment in a smoke filled tunnel. Work in progress. Lund: Lund University.

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Andersson, A. and Carlsson, E.S. (2012). "Structures in Underground Facilities – Analysis and Dimensioning of a Concrete Column's Capability of Withstanding Extraordinary Fire Loads", Master Thesis, Mälardalen University.

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THE METRO PROJECT

The report compiles the results from the METRO project. The different parts of the project; design fires, evacuation, integrated fire control, smoke control, extraordinary strain onconstructions and fire- and recue operations are presented separately.

The most complicated and expensive part of the project was the performance of the large scale fire and explosion tests in the Brunsberg tunnel. The maximum heat release rates measured from the metro wagon was 77 MW.

The main results from the project are new recommendations regarding design fires in mass transport systems, identification of key factors for fire and smoke spread in tunnels and at stations as well as regarding the difficulties for disabled persons to evacuate from train in tunnels, new recommended types of way guiding systems, safer design in case of explosions in trains and evaluation of the fire and rescue services possibilities and limitations in underground mass transport systems.

The METRO project is a three year research project, financed by the Stockholm Public Transport, the Swedish Fortifications Agency, the Swedish Civil Contingencies Agency, the Swedish Transport Administration, the Swedish Research Council Formas and the Swedish Fire Research Board.

The project is unique as nine Swedish organizations work multidisciplinary with the same aim – to make metro systems safer. The organizations are; Mälardalen University, SP the Technical Research Institute of Sweden, Lund University, FOI the Swedish Defense Research Agency, the Swedish Fortifications Agency, the Swedish National Defense College, Gävle University, the Stockholm Public Transport and the Greater Stockholm Fire Brigade.

A study from MERO

This study is published within the MERO research area (Mälardalen Energy and Resource Optimization) at Mälardalen University. The research within MERO is directed towards various aspects of a sustainable society, with particular focus on the optimization and protection of community resources and infrastructure. The research groups within the area are mainly specialized in energy efficiency, resource conservation, design of systems and processes, remediation of contaminated land and fire safety in underground facilities. A common denominator is all aspects of optimization and risk management, where modeling, simulation, validation and applied mathematics are important tools. Responsible research leader is Professor Erik Dahlquist.

http://www.mdh.se/forskning/inriktningar/mero

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