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Metro Vehicle Blast Testing: Mitigating the effects of Terrorist Attacks on Metro Vehicles.

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Abstract

Over recent years the mechanics by which terrorist attacks are carried out have changed leading to an increased threat of un-forewarned attacks on transport systems. One of the counter-measures which can be implemented to reduce the risk of such attacks is by making transport systems a less attractive target for terrorists. This can be achieved by mitigating the effect such attacks have on passengers, staff and metro infrastructure.

The aim of the European Framework 7 project “SecureMetro” is to increase the safety and security of metro vehicles from terrorist attacks by explosives through material choice and vehicle design, thereby increasing resilience and reducing the impact of attacks on passengers, staff, infrastructure and property.

This paper provides a review of the impact of past terrorist attacks on metro vehicles and systems over the past 60 years (1960-2010), describing the attack methodology and the immediate and subsequent effects on the passengers, staff and infrastructure. It describes the set-up and execution of an explosives test on a decommissioned Metro de Madrid vehicle and discusses the response of the vehicle structure to the blast. It makes design recommendations to achieve more inherently secure vehicles and proposes key areas where the choice of materials and design can mitigate the effects of blast attacks.

Keywords: Blast; Metro; Security; Firebomb; Terrorist attack; Explosives;

1. Terrorist Attacks on Rail Systems.

1.1. Introduction

With almost 200 metro systems worldwide, and hundreds of millions of passengers carried annually [1], underground or metro systems by their open-access nature are at risk from terrorist attack. Such concentrations of people in contained environments make the systems especially vulnerable to attack through the use of explosives and improved explosive devices [2].

In order to effectively tackle the threat posed by terrorism to our underground networks, it is essential that operators and manufacturers have a thorough understanding of the past attacks perpetrated against railway systems and the likely attack methodologies terrorists may adopt in the future. This means identifying preferred tactics, location, devices, means and procedures, in order to provide pre-emptive answers to be adopted in case of terrorist attack.

1.2. Past attacks

One of the key objectives of the SecureMetro project was to undertake a study to review and analyse past terrorist attacks to identify trends in methodology, location and severity. The objective of this study was to provide an overall assessment of the terrorist attacks perpetrated against rail-based public transport systems in the last fifty years (1960-2010), focusing in particular on underground metro systems. For the purposes of this study, terrorist attacks have been defined as violence calculated to create an atmosphere of fear and alarm to coerce others into actions they would not otherwise undertake, or refrain from actions they desired to take and are generally carried out in a way that will achieve maximum publicity. Therefore, the study does not consider attacks against
transport systems and infrastructure perpetrated by armed forces and military factions during conventional armed conflicts.

To undertake this study, data was gathered from the RAND Corporation’s Database of Worldwide Terrorism Incidents (RDWTI) [3] and from the University of Maryland’s Global Terrorism Database [4]. These two databases have collected, classified and catalogued terrorist events which have occurred worldwide since the 1960s.

The data was filtered to focus on attacks perpetrated on metro systems, including vehicles and infrastructure to better meet the requirements of the SecureMetro project. Then, common information relating to the terrorist attacks was extracted, such as: year, country, target, tactic, weapon, number of fatalities, number of injuries and perpetrators. The data was analysed with two specific timeframes in mind: 1960-2010 and 2000-2010. Focusing in on this most recent decade allowed the project to extract data which better reflected current trends in terrorist attacks.

Concerning tactics adopted to attack train and subway systems (Figure 1), it was noted that bombing is largely the preferred and more common way to carry out attacks, accounting for more than half of the total events recorded (57%) in the period 1960-2010. Sabotage follows (20%) and then armed attack (7%), and arson (5%). For the period 2000-2010 (Figure 2), there is little change in the statistics, with bombing, sabotage, armed attack and arson having 58%, 23%, 6% and 6% respectively. This suggests that for the foreseeable future, bombing remains the primary terrorist attack methodology for use on rail transport systems.

![Figure 1: Types of terrorist attacks on rail systems and infrastructure between 1960 and 2010.](image1)

![Figure 2: Types of terrorist attacks on rail systems and infrastructure between 2000 and 2010.](image2)

Of the tactics adopted, bombing is the deadliest with 70% of the total fatalities occurring as a result of bomb attacks. This trend is also reflected in the number of injuries with 77% of the total people wounded by bomb attacks.

1.3. A Focus on underground rolling stock
Bombing accounts for roughly two-thirds of the total violent activities perpetrated against metro vehicles. In the past vehicles have been largely subjected to single assaults, while multiple simultaneous attacks on vehicles represent only a minority option. However, what seems to be particularly relevant is that the majority of multiple attacks identified from the data are concentrated in the period between 2000 and 2010.

Table 1: Attacks on subway systems.

<table>
<thead>
<tr>
<th></th>
<th>Total Attacks</th>
<th>Attacks on Vehicles</th>
<th>% of Total</th>
<th>Fatalities on Vehicles</th>
<th>% of Total</th>
<th>Injuries on Vehicles</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subway</td>
<td>82</td>
<td>29</td>
<td>35%</td>
<td>90%</td>
<td></td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>Subway EU</td>
<td>35</td>
<td>11</td>
<td>31%</td>
<td>100%</td>
<td></td>
<td>92%</td>
<td></td>
</tr>
</tbody>
</table>

Of the 833 attacks investigated, 82 have been perpetrated against subway systems across the world, with 35 occurring in European Union countries. It emerges that the vast majority of fatalities and injuries due to attacks in subway systems (90% in the case of fatalities and 67% in the case of injuries), actually occurred on metro vehicles. Table 1 clearly shows such trends, proving the importance of addressing the issue of metro vehicle resilience to blast attacks.

2. Understanding the impact of blast on metro vehicles

2.1. Introduction

To gain an understanding of how a terrorist bomb attack could affect metro rolling stock, the SecureMetro project undertook a blast test on a decommissioned Metro de Madrid vehicle. The aim of this test was to provide insight into key areas of metro vehicles which may be severely damaged or destroyed as a result of the blast. Areas of primary concern were: Vehicle primary structure; Glazing fragmentation; Impact on doors; Driver’s cabin; Under floor equipment retention; Interior fixtures and fittings.

The vehicle chosen for the test was a Metro de Madrid Series 5000 vehicle as shown in Figure 3.

![Figure 3: Metro de Madrid 5000 Series vehicle on test site.](image)

The test setup was based on an attack scenario devised by the project which was deemed typical of a potential attack on a metro vehicle. The following configuration was chosen:

**Device type and size** – Due to security reasons the type and size of the devise cannot be released in this paper, the charge was chosen so that it was representative of past attacks and was agreed to be typical of what could potentially be brought on-board.

**Location** – The charge was located along the centreline of the vehicle, and placed in the gangway between the doors towards the rear of the vehicle (second to last doors). This central location was chosen to simplify the blast simulation activities, and it was acknowledged that a number of other locations could have been chosen which would equally have represented an attack.
Vehicle configuration – All hazardous materials were removed from the vehicles, all liquids were drained and tanks depressurised. The doors, both external and internal, and windows were all in the closed position. All internal and underframe equipment, including bogies, were retained.

Instrumentation – Pressure sensors were located at points extending away from the blast source to determine the progression of the blast wave as it moves away from the vehicle. High speed cameras (up to 3000 frames per second) were located around the periphery of the test site to capture the trajectory of debris, and marker boards were positioned to assist in determining the velocity of objects during the blast.

Conducting the test - The test was performed under controlled conditions at the Health & Safety Laboratories in Buxton, UK. It was conducted in the open air and in dry conditions.

3. Results of the blast test.

Figure 4 shows the early stages of the blast test on the Metro de Madrid vehicle. Captured at approximately 1/2500 sec after detonation, a fireball can be seen exiting the vehicle as the blast wave progresses through the vehicle and enters the driver’s cabin. The roof bulges upwards and the air vents are becoming detached. Underneath the vehicle the blast is just visible as it punches a hole in the floor allowing the initial blast flames to exit (A).

![Figure 4: Blast test in progress (1/2500 sec).](image)

At approximately 2/2500 sec after detonation (Figure 5) it can be seen that the doors closest to the charge (A) are removed from their mountings and thrown upwards and outwards away from the vehicle.

![Figure 5: 2/2500 sec after detonation](image)

The doors eventually came to rest 50m from the vehicle. Four of the five air vents on the roof (B) have become detached and projected vertically into the air. Glazing is shattered and window seals (C) are
stripped from the vehicle, eventually travelling 20m away from the blast source. The blast wave has penetrated the driver's cabin and caused the driver's windows (D) to become removed from their housings, but have remained as single components due to the driver's bulkhead and door resisting the penetration of the blast wave.

4. Analysis of the metro vehicle post-blast.

4.1. Windows/Glazing

The vast majority of the windows on the vehicle were shattered or became detached from their mountings. They are the primary source of fragments and could lead to injuries or fatalities in passengers external to the vehicle. Windows should ideally not fragment, but be able to absorb at least partially the energy of the blast wave through plastic deformation.

4.2. Doors

Modern metro vehicle designs have removed most of the interlocking doors between carriages creating open “boa” type vehicles where passengers can easily walk between carriages. This design philosophy can have both beneficial and detrimental effects. High over pressures are reduced (due to removal of interlocking doors) however the blast effect can influence a greater volume of the train without doors present, travelling the full length of the vehicle. The impact of this pressure build-up can be seen clearly in Figure 6 where the doors closest to the drivers bulkhead (A) have suffered more severe damage (and detachment) than those closer to the blast point. It is likely that the observed damage to the doors would hinder rescue efforts and restrict egress routes for passengers.

![Figure 6: The post-test condition of the metro vehicle.](image)

4.3. Walls

The majority of the internal walls of the carriage exhibited little deformation, being able to absorb the energy of the blast through plastic deformation, without breaking into pieces. Some fracturing occurred in the vicinity of the blast point, but detachment or fragmentation was not evident.

4.4. Roof

All but one of the five air vents on the roof became detached. There was localised bulging in the roof structure directly above the blast point.

4.5. Internal fixtures and fittings

The seats and handrails were slightly damaged but remained in situ. The majority of the internal debris came from the ceiling, with covers from the lights and vents, panelling and insulation becoming detached coming to rest in the gangways and aisles. The volume of debris in the gangways from this test would be likely to hinder access and egress.

4.6. Under floor equipment
Despite the proximity of the blast device to the under floor equipment, there was little detachment of equipment in evidence. Only one heat exchanger became partially separated from the main structure, while an air reservoir directly beneath the detonation point remained securely in place. This is of particular significance as a detonation on a moving vehicle could lead to derailment should the under floor equipment become detached.

5. Conclusions and recommendations

The research of the SecureMetro project has revealed not only an increase in the frequency of terrorist attacks on rail systems, but also in the magnitude of loss associated with such attacks. The findings also reveal that when attacks are perpetrated against metro systems, there is a strong tendency to target the vehicles as opposed to the surrounding infrastructure. Whilst detection and prevention remains key to reducing the effectiveness of terrorist attacks, the test on the Metro de Madrid vehicle has highlighted a number of key areas within the metro vehicle structure itself which could be modified to improve their resilience to the effects of blast and firebomb attacks.

Recommendations for future metro vehicles include:

- Reinforcing the driver's bulkhead to protect the driver who can act as a focal point for passengers and emergency crews post attack.
- Reduction in the level of glazing fragmentation to reduce injuries both on board the vehicle and on surrounding platforms.
- Reduction of debris in gangways post blast could be achieved by implementing a tethering system which would connect panels and equipment (lights, speakers, etc.) to the main structure of the vehicle which is largely unaffected by the blast.
- Door detachment could be improved to ensure that even when buckled they can be easily removed to improve access and egress.

A pragmatic approach is needed when defining design criteria to mitigate terrorist attacks. The recommendations outlined in this paper will need to take into account some wider considerations of the industry such as; cost effectiveness, the potential for an increase in the mass of the vehicle and the practicality of implementing such solutions within existing metro tolling stock. Balancing these criteria will be key to designing a successful blast and firebomb resilient vehicle.

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