O'Neill C, Robinson AM, Ingleton S.

Mitigating the Effects of Firebomb and Blast Attacks on Metro Systems.

***Procedia: Social and Behavioral Sciences* 2012, 48, 3518-3527.**

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia - Social and Behavioral Sciences 48 (2012) 3518 – 3527

Procedia
Social and Behavioral Sciences

Transport Research Arena – Europe 2012

Mitigating the Effects of Firebomb and Blast Attacks on Metro Systems.

Conor O'Neill[a,*], A. M. Robinson[a], Steve Ingleton[a]

[a] *NewRail. School of Mechanical & Systems Engineering, Newcastle University, NE1 7RU, UK*

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 and firebombs through material choice and vehicle design, thereby increasing resilience and reducing the impact of attacks on passengers, staff, infrastructure and property.

Metro vehicles have been selected for study because these are often crowded, representing a high profile target for terrorists aiming at mass casualty attacks. Current approaches to security on these systems are largely managerial (enhanced vigilance, detection of concealed items, depot security) or use searches and screening (e.g. detection of explosives using dogs). The greatest resilience to attack is provided through a multi-layered system of security. SecureMetro adds an additional layer of protection to the system, which will remain effective even if others are not successful.

This paper reviews the impact of past terrorist attacks on metro vehicles and systems, describing the attack methodology and the immediate and subsequent effects on the passengers, staff and infrastructure. It discusses the response of infrastructure and support systems relating to these attacks. It also 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

---

[*] Corresponding author.

E-mail address: conor.oneill@ncl.ac.uk.

doi:10.1016/j.sbspro.2012.06.1315

1. Terrorist Attacks on Rail Systems.

1.1. Introduction

Railway and subway systems are open to millions of passengers worldwide and such concentrations of people in contained environments make the systems especially vulnerable to terrorist attack through the use of both conventional explosives and unconventional weapons.

Even when they are not particularly violent or atrocious, terrorist attacks against public transportation systems in urban environments generally cause diffuse panic, alarm and suspension of vital functions, which are the traditional goals of terrorism.

In order to effectively tackle the threat posed by terrorism and other forms of violent crime, it is essential that operators 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 acknowledging 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 analyze 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) and from the University of Maryland's Global Terrorism Database[‡]. These two databases have collected, classified and catalogued terrorist events which have occurred worldwide since the 1960s.

The data was initially filtered to rail related attacks, 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. Where available, further details (i.e. type of bomb, suicide mission, simultaneity with other attacks) were noted to better understand the potential impact of attacks on metro systems. The data was analyzed 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.

Since 1960 train and subway systems have been object of 833 attacks (Fig. 1), which killed a total of 3457 people and injured 15887[§] (10682 excluding people injured during the 1995 Tokyo sarin attack).

[†] *Database of Worldwide Terrorism Incidents* website: http://www.rand.org/nsrd/projects/terrorism-incidents/about/

[‡] *Global Terrorism Database* website: http://www.start.umd.edu/gtd/

[§] This figure is strongly skewed by the high number of injured recorded in the 1995 Tokyo sarin attack, which accounts for nearly one third of the total injuries recorded in our chronology. The total injured is subject to contestation and revisions (see RAND Corporation's *Securing America's Passenger-Rail Systems*, p. 13/14), so for the purposes of this paper, the total injuries toll shall exclude the 1995 Tokyo sarin attack figures.

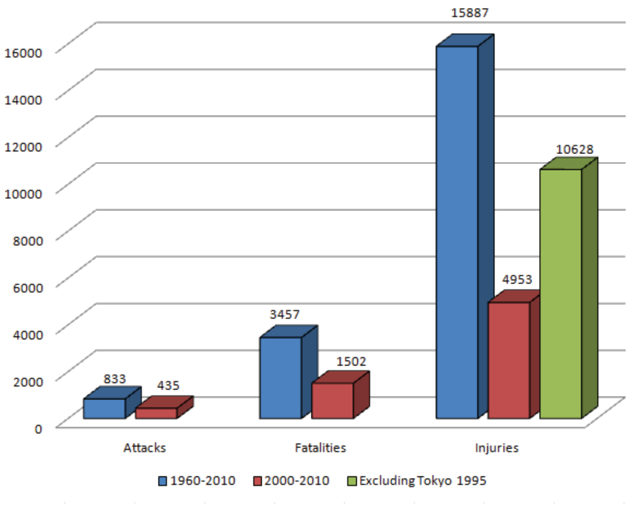
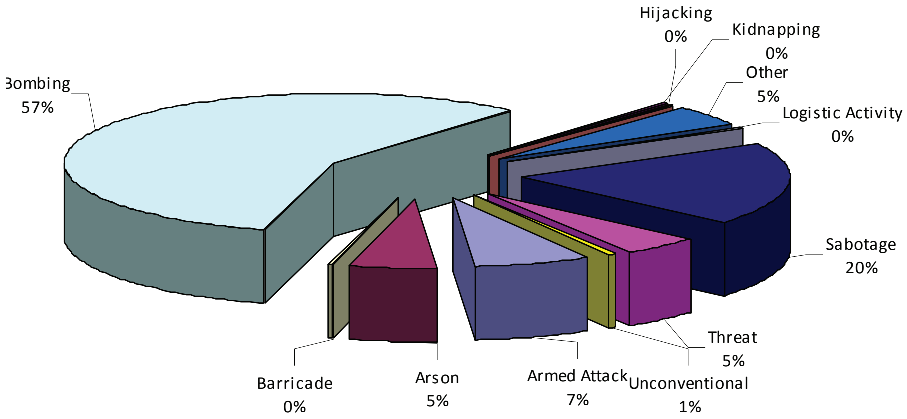


Fig. 1. Number of attacks, fatalities and injuries.

The data collected showed an increase in attacks and casualties experienced in the last decade (2000-2010). In particular, more than a half of the total (52%) have been carried out during the last 10 years. The same period also recorded 43% of total fatalities and 46% of total injuries.

Concerning tactics adopted to attack train and subway systems (Fig. 2), 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, there is little change in the statistics, with bombing, sabotage, armed attack and arson having 58%, 23%, 6% and 6% respectively (Fig. 3). This suggests that for the foreseeable future, bombing remains the primary terrorist attack methodology for use on rail transport systems.



[**] Bombing is defined as a bomb attack when there is the clear intention to procure harm to people. Where bombs are used explicitly to create damage and affect the regular course of the transport activity we classify it as sabotage.

Fig. 2. Types of terrorist attacks on rail systems and infrastructure between 1960 and 2010.

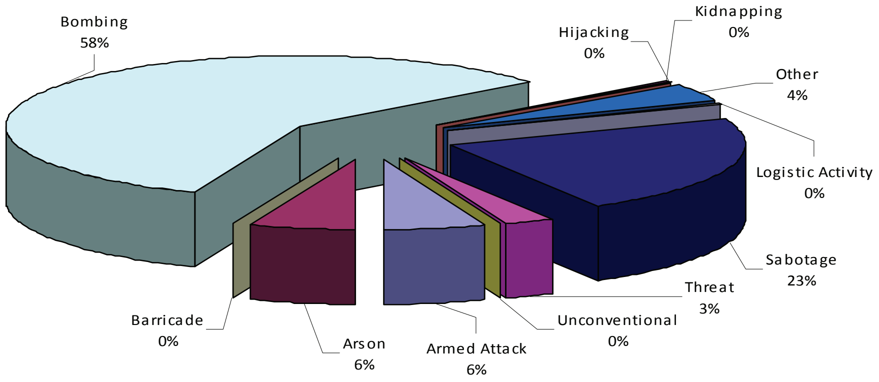


Fig. 3. Types of terrorist attacks on rail systems and infrastructure between 2000 and 2010.

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 Subway Vehicles

From the data studied, tracks and vehicles are undoubtedly the preferred locations for attacks. The number of attacks on vehicles and tracks are roughly similar in number for the time periods studied, but those on vehicles are considerably more lethal. 73% of the fatalities have occurred while travelling on train or subway carriages, while only 12% of the fatalities were due to attacks on tracks. It is interesting to note that attacks in stations, although numerically less frequent than those on tracks, have a higher mortality percentage (15%).

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.

	Total Attacks	Attacks on Vehicles	% of Total	Fatalities on Vehicles	Injuries on Vehicles
Subway	82	29	35%	90%	67%
Subway EU	35	11	31%	100%	92%

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 security.

1.4. Future Threats – Fire & Blast

Focusing on the period 2000-2010 it is clear from the data that bombing is the preferred attack method and this trend is likely to continue into the next decade. Of the seven attacks carried out during this period on subway vehicles, four have been carried out by suicide attackers: Daegu arson attack on the 18th February 2003; Moscow bombing on the 6th February 2004, London bombing on the 7th July 2005 and Moscow bombing on the 29th March 2010. It was noted that all four of these attacks were carried out at morning rush hour in order to maximise the number of fatalities and injuries among passengers. Concerning the positioning of the devices on the train, most devices were located in the proximity of the doors where passengers congregate to alight or board the vehicle.

To better understand the key concerns of the rail (metro) industry regarding potential terrorist attacks a questionnaire was distributed to stakeholders within the industry for their feedback. A total of 13 respondents provided their insights into future threats and the findings are summarized as follows:

Table 2. Findings of the industry questionnaire.

Question posed	Highest ranking response
Most severe threat	Explosive device
Most probable threat	Explosive device
Most vulnerable target	Multi-modal terminals
Primary aim of attack	Loss of life
Device type	Improvised explosive device
Attack type	Multiple targets

The responses reveal that the industry feels the primary threat to the rail systems comes in the form of explosive devices. And whilst the threat of firebomb or arson attack was deemed to be relatively low, the stakeholders unanimously agreed that the lethality of such an attack would be high.

Although historical data and that gathered from the stakeholders provide a clear indication for security concerns today, it should be noted that terrorists are dynamic and flexible entities whose attack patterns change rapidly and without warning.

2. Structural Design to mitigate effect of attack

The SecureMetro project is looking at the structural design and material choice to better mitigate the effects of blast attack. Whilst it is not practical to create a bombproof metro vehicle (due cost, weight, ease of access issues, etc.) it is possible to modify the response of the structure to reduce the impact a blast has on both the structure and its passengers.

The structures in the immediate vicinity of a bomb detonation are exposed to both blast and fragment loading, which means that several types of loading effects must be considered, in particular:

- **Shock waves**: After a blast wave strikes a surface, high-velocity shock waves, will continue to pass through the structure.
- **Fragmentation**: The impact and/or penetration of shrapnel.
- **Fire and heat**: Structures may be exposed to fire and heat sources either as a result of the initial explosion or from secondary fires and explosions.
- **Blast wind**: At the explosion site, a vacuum is created which will almost immediately refill itself with the surrounding atmosphere. As a result a high-intensity wind occurs which may cause fragmented objects and debris to be drawn back towards the source of the explosion.

Internal explosions (such as those within an underground train) can produce complex pressure loading profiles as a result of two loading phases; the first loading phase results from the blast overpressure reflection and, due to the confinement provided by the structure, a second loading phase of re-reflection will occur. Depending on the degree of confinement of the structure, the combined effects of the resulting pressures may cause different degrees of damage to the structure. On the basis of the confinement effect, target structures can be described as either vented or un-vented with the loading of the structure varying depending upon its shape and its ability to allow venting of detonation products. An un-vented structure must be stronger to resist a specific explosion yield than a vented structure where some of the explosion energy would be dissipated, for example by the breaking of window glass (in the case of a rail vehicle). Venting following the failure of windows generally reduces the peak values of internal pressures, however venting within a confined space (such as a tunnel) can also lead to complex loadings forcing parts of the vehicle structure back into the vehicle, as can be seen in Fig. 4.

Fig. 4. (a) &(b) Part of a metro vehicle door forced into the compartment due to reflected pressure waves from surrounding tunnel infrastructure.

2.1. Windows/Glazing

They are the primary cause of fragments and injuries, since the multiple reflections of the blast wave cause the glass debris to be projected at high speed inside the carriage, hitting and penetrating passengers. Windows should ideally not fragment, but be able to absorb at least partially the energy of the blast wave through plastic deformation. Particular attention should be paid also to the windows frames, which should be able to keep the glass attached to the vehicle structure, avoiding the whole glass and the frame to be projected either outside, when stopped at a station, or inside, when in a tunnel.

2.2. Interlocking 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.

2.3. Walls

The walls of the carriage should be able to absorb the energy of the blast through plastic deformation, without breaking into pieces and to limit the reflection of the blast wave inside the carriage. Ideally the materials used in the walls of the carriage should be able to absorb the energy of the blast through controlled deformation, either at a material level or through joint design.

2.4. Roof

The blast wave generates a negative pressure which can effectively suck components that are not suitably attached to the surrounding structure towards the epicenter of the blast. Roof materials should reflect those used in the walls (i.e. energy absorbing) but should also focus on the joining methods and materials used between components. Depending on the location of heavy equipment (such as HVAC) it may be necessary to reinforce or protect key support structures for this equipment to avoid collapse of the roof panels.

2.5. Seats

The blast wave can cause the seats to disintegrate into high velocity projectiles, killing or injuring passengers. Ideally, seats should be arranged so as to be affected as little as possible by the blast, in which case longitudinal seating arrangements are preferable. Their connection with the carriage structure should be designed so that it is able to resist or absorb part of the blast wave energy. Material selection should focus on energy absorbing materials (where possible based on the seating design) but mainly on energy absorbing joints both within the seat and between the seat and vehicle structure. The joints should ideally enable deformation for energy absorption but avoid complete failure to maintain the seating within the vehicle structure. The seats themselves should have minimal parts to reduce the material available for fragmentation.

2.6. HVAC and other heavy equipment

Heat, ventilation and air-conditioning equipment have a significant mass and size. Typically located on the roof of the carriage, the negative pressure generated by the blast can in fact cause them to fall inside the carriage, hitting the passengers. Heavy equipment should be therefore placed on the floor or below it, shielded by the floor and the heavy bogies structures, in order not to fall on passengers. Failing that, the structure which supports the equipment should be suitably reinforced.

Should a device be detonated on the floor of a metro vehicle, the blast is likely to penetrate the floor and the blast wave vent outwards underneath the vehicle, causing damage to bogies and equipment. Equipment detaching from the underside of the train is highly likely to cause derailment and damage to the infrastructure. In January 2003 a London Underground Central Line train derailed due to the detachment of the traction motor from the vehicle. The extent of the damage to the infrastructure was detailed in a London Underground interim report of the incident:

> *"The motor also damaged the track in the tunnel; smashing several sleepers and insulating pots on the power rails. The derailment also pushed the running and power rails out of their mountings for around 15 metres. The sides of the derailed cars also inflicted damage on the tunnel cable brackets, associated cables and tunnel telephone wires. Some debris appears to have entered the passenger saloon. The platform edge was damaged for about 15 metres from the rear tunnel wall."* (London Underground 2003)

By reducing the likelihood of the traction motor detaching in the event of a blast will minimise the possibility of derailment and damage to infrastructure. This can be achieved through local strengthening of the vehicle structure.

2.7. Critical systems

Critical systems should survive a blast: in particular lights and communication systems should remain operative, in order to avoid injuries when trying to leave the train in complete darkness and without any guidance. They should therefore be shielded, for example placing cables inside metal tubes and/or under the carriage floor. A tethering system may be employed to ensure that small but heavy objects, such as speakers and emergency pull handles, do not become completely detached from their housings during a blast.

2.8. Driver cabin

One of the key findings from investigations into the London Underground bombings of the 7th July 2005 was that following the incident there were no clear means of communication between the passengers and the driver.

> *"Passengers on the three bombed trains were unable to communicate with the drivers of the trains to alert them to the explosion. Had they been able to do so, they might have been able to help the transport and emergency services establish what had happened in the minutes following the explosions."*(Greater London Authority 2006).

Materials similar to those used in the walls and roof panels can be suggested for protection of the bulkhead between drivers cabin and passenger compartment. Energy absorbing and penetration resistant materials can be used in a similar format to the wall protection; however it is more likely that the full extent of the bulkhead will be reinforced. In case of a blast the driver should be able move the train to the closest station in order to let the passengers leave the train safely and the rescuers to help the injuries. Besides this would be possible only if also electric, pneumatic and hydraulic systems are still in service after the blast, in order to move the train: they should be therefore protected.

3. Arson and fire suppression/prevention

The events of 18th February 2003 in the subway system of Daegu, South Korea highlight the rapidity with which fire can spread and the high number of fatalities such an event can bring about. After an arsonist set fire to four litres of flammable liquid, it spread quickly to all six coaches of the train within two minutes due to the highly flammable interior of the train. The seats, flooring and advertisement boards were not manufactured from fire proof materials but composed of flammable fibreglass, carbonated vinyl and polyethylene. The fire also spread to train 1080 travelling in the opposite direction which stopped alongside. At least 192 people were killed and approximately 148 injured (National Emergency Management Agency 2004).

Whilst it is now becoming the norm to include fire resistant materials in metro vehicles (such as compliance to CEN/TS 45545) there remains the opportunity to introduce fire suppression technology on board the vehicles.

Deploying an effective fire suppression system can form a key ingredient in the fire safety design of a train carriage. Constraints on the amount of water that can be stored on a train for a sprinkler system, and a ban on the use of ozone depleting Halon 1301 would make water mist technology a practical alternative for fire control in trains. In comparison to a sprinkler spray, the smaller sized water mist droplets offer larger surface area for the same amount of water, allowing faster evaporation of the droplets, and more effective heat extraction from a fire. The mist vapour dilutes the concentration of oxygen as well as of the pyrolysis fuel vapour, thus slowing or arresting combustion. Water mist can also block the thermal radiation and pre-wet other combustibles in the vicinity to reduce their temperature and delay the ignition.

4. Key systems to improve survivability

Survivability of certain key systems on the metro vehicle will allow the team in charge of the crisis management to gather information on the status and location of the damaged train or trains and their occupants. This is of paramount importance in order to efficiently manage the rescue operations. For the surviving passengers, the post-blast functionality of certain systems will allow them to assess their condition, help themselves and each other, and allow rescue access and evacuation.

The SecureMetro project has identified the following list of key systems which should be designed to remain wholly or partially operational post-blast:

- **Lighting**. The first need of the survivors is to assess their condition, reach for safe places, try to communicate with the outside world and facilitate rescue. Blast-resistant emergency lighting therefore ranks very high on the list of priorities. Provision should be made to ensure visibility through smoke and soot. Flashlights should be available (Greater London Authority 2006).
- **Driver**. The presence of the driver is of paramount importance in the case of an emergency, not only providing the victims with a person who is knowledgeable of emergency procedures, the train and the underground system itself, but also acting as a point of contact to relay updates and commands to passengers following the incident. Moreover, the presence of a knowledgeable person relieves the sense of helplessness. In automatic metro systems, the same function can be fulfilled by the control centre, so in this case the intercom and the associated radio link take a particularly vital role.
- **2-way radio communications**. This link is used both to allow the persons in charge of the crisis management to gather information from the driver or the passengers, and to communicate information and instructions. The role of communicating with the outside world is important not only from the practical point of view, but also to relieve the sense of powerlessness and isolation.
- **Door operating systems**. The capability to egress the train after a blast is unquestionably a basic requirement, also to avoid the feeling of being trapped. As such, the doors slides must be guaranteed to be operative (also in taking measures against the blockage of the mechanism by pieces of glass, for example), the unlocking mechanism must be usable even if unpowered and doors should be able to be operated from inside the carriage.
- **Backup of the surveillance data** for forensic purpose. This functionality is a mere backup of data recorded before the blast: it has not been found necessary to keep gathering data of the explosion and after, which would require hardening the cameras and microphones.

5. Conclusions

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 remain key to reducing the effectiveness of terrorist attacks, the SecureMetro project 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.

To identify technology solutions for metro vehicles, the SecureMetro project shall focus on the improving the response of the vehicle structure in the following areas:

- Reinforcing the driver's bulkhead.
- Reduction in the level of glazing fragmentation.
- Reduction of projectiles from walls and ceilings.
- Lessen the likelihood of equipment detachment.
- Protection of key systems.

A pragmatic approach is needed when defining design criteria to mitigate terrorist attacks. The technologies that the project shall focus on 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 technologies within existing metro vehicle structures. Balancing these criteria will be key to designing a successful blast and firebomb resilient vehicle.

6. Recommendations for future work

The SecureMetro project has currently identified a series of small and large scale blast tests to prove out the technologies. Panels testing shall provide the data required to support the blast simulation activities, whilst two full scale tests shall define the response of current technology and substantiate the effect of the identified blast mitigation technology.

Acknowledgements

The authors would like to thank the European Commission for supporting the funding for the "*SecureMetro – Inherently secure blast resistant and fire safe metro vehicles*" project, and would also wish to thank all participating project partners.

References

Greater London Authority, 2006. *Report of the 7 July Review Committee*, Available at: http://legacy.london.gov.uk/assembly/reports/7july/report.pdf.

London Underground, 2003. *Derailment at Chancery Lane - Interim Report*, Available at: http://www.railwaysarchive.co.uk/documents/HSE_ChanceryLane2003_Interim.pdf.

National Emergency Management Agency, 2004. *Fire in Daegu Subway.*, Daegu, South Korea. Available at: http://eng.nema.go.kr/sub/cms3/3_4.asp.