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The need for developing an effective and acceptable engineering response to terrorist attacks on railway systems

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Abstract

In recent years terrorism has affected rail transport in Europe and elsewhere in the world. This paper gives a brief historical review of terrorist attacks on rail systems and the counter-terrorism security measures which have evolved in response. The possibilities for 'designing-in' resilience to a terrorist attack are examined, and some inputs by which engineering may have a positive long term impact on the security of rail systems are identified. The paper reviews media articles, academic papers and reports, government material and the results of interviews with security managers on rail systems. It considers the required performance of counter-terrorism measures with regard to the safety of passengers and staff, the physical processes taking place during a bomb explosion, and also highlights several issues that will affect how counter terrorist measures are 'designed-in', including public and business acceptability, reduction of threat and cost-effectiveness.

Keywords: rail, counter-terrorism, resilience, design, security, risk assessment

1 Introduction

Rail systems have been faced with terrorism since their inception in the 19th century, a good example being the Native American attacks on the railroads of the US. However, in recent years the emergence and evolution of new threats has brought awareness of terrorism to the fore. In the UK, the IRA campaign that spanned several decades has had a significant impact, as did the July 2005 attacks in London. Elsewhere, other mass casualty events such as the sarin gas attacks on the Tokyo subway in 1995, the Madrid train bombings in 2004 and the November 2009 Nevsky Express bombing received worldwide attention; many other countries have suffered domestic terrorism which is less widely reported.

Overall, the number of casualties and the economic costs of preventing and recovering from terrorist attacks are low (since the frequency of occurrence is very low) in comparison to other events such as accidents or railway crime. However, people's fear of terrorism can greatly increase the perception of the threat and consequences of an attack. Although some analysis concludes that current counter-terrorism responses are out of proportion to the risk [1], the wider implications of an attack must be considered and a balance found which is acceptable in terms of its impact on the system, on costs, and on wider society including the travelling public.

From an engineering perspective, the issue arises of whether a rail system can be designed so as to be less vulnerable or able to mitigate the damage produced by an attack, i.e. can the design of stations, vehicles and infrastructure increase resilience to a terrorist attack? Features which may be 'designed-in' are dependant on the site and the threat faced, but guidance from the Royal Institute of British Architects illustrates the range of measures which may be considered for a station building. For example, glazing may be designed to resist blast, or so that broken fragments of glass are retained rather than becoming projectiles. Unauthorised vehicle access or approach may be prevented through careful landscaping rather than obvious barriers, and structural features which may exacerbate the effects of an explosion can be avoided [2]. This paper considers application of this type of design and engineering approach for counter-terrorism security, rather than strictly operational approaches to this problem (such as policing); however, input at the design stage can improve the effectiveness of such day-to-day security operations. The term 'resilient design' is used to encompass the various approaches which can increase security to a range of threats through designing to reduce vulnerability, mitigate damage, and to quickly recover to normal operation.

2 Terrorism on rail systems

2.1 Trends of previous attacks

Detailed analysis of past attacks and future threats is usually carried out by government intelligence agencies, rather than the railway systems themselves; in the UK this is carried out by the Joint Terrorism Analysis Centre (JTAC) which includes representatives from sixteen government departments and agencies. Nonetheless, it is useful to take a brief look at previous attacks to inform the design of countermeasures. The US Department of Homeland Security START database lists 328 reported terrorist incidents across the globe against transport targets [3] in the period 1998 to 2004 (the most recent period with complete data at the time of analysis). Of these, 86 were directed against rail systems (including subways and light rail), approximately 26% of the total. This is greater than the 59 (18%) attacks directed against civil aviation; there were also 14 (4%) attacks against maritime transport and 169 (52%) against road transport. Figure 1 summarises the methods involved, both for attacks on rail systems, and also a comparison against all recorded attacks.

The majority of terrorist attacks against rail have been bombings, while the proportion of sabotage and arson incidents on rail systems are similar to those recorded for all terrorist attacks (note that only terrorist incidents proper are included here, rather than all criminal activity on rail systems). There have, thankfully, been too few CBRN (chemical, biological, radiological or nuclear) events recorded for patterns or trends to emerge, and events such as the assault on a train in Angola in 2001 [4] and the train hijackings in Holland in 1975/1977 [5] are notable individual events of types which have been uncommon across railways worldwide.

The distribution of attacks between railway track, stations and passenger trains is shown in Figure 2 illustrating that there is a roughly even spread of target choice. The classification here refers to where the attack was carried out, for example where a bomb was planted. Many of the ‘track’ events were bombs planted on the tracks and detonated as a target train was passing (rather than simply to damage the track), however they are classified as such to distinguish them from bombs planted on the trains themselves. The ‘infrastructure’ category covers bridges, power supplies and catenary, as well as other railway buildings outside of stations.

Different impact results depending on the choice of attack method and target, as summarised in Table 1. There are two major incidents during the period considered that have significantly more casualties (including fatalities) than other events in the table: the assault on a train in Angola in 2001 (419 casualties) and the 2004 Madrid train bombings (2032 casualties). As expected from the frequency they occur, bombings account for the majority of casualties. The choice of target is also significant; although there is a roughly even split in the number of attacks between targets, passenger trains account for the majority of casualties, followed by stations, with very few casualties resulting from other attacks. However, this only considers casualties as a measure of the seriousness of an attack, it does not show the likely disruption during recovery, economic impact, or the change in public perception of rail travel safety.

Looking at these past attacks, the most important threat to rail systems has been a bombing that targets passenger trains; this has been the most common method of attack, with the highest number of casualties associated with the target. In most cases, there will be a good correlation between casualties and disruption/economic impact of an incident (exceptions include key infrastructure or special events at otherwise unimportant locations). There is also a significant threat to stations, again from bombings. If these trends continue this suggests that these should be seen as a priority when investigating design to build counter-terrorism features into the rail system. However, history also shows that attacks will evolve to overcome mitigating or preventative measures, so designing for rapid recovery, and to support organisation of evacuation in emergencies of any cause is also vital.

2.2 Current approaches to transport terrorism

The experience gained from the IRA campaigns of the 1970s to 1990s has underpinned the current transport counter-terrorism strategies in the UK. In addition, since the 1995 Tokyo sarin gas attack, attacks in the US on September 11th 2001 and the London transport bombings in July 2005, transport operators and local authorities have considered planning and contingencies for mass casualty events in greater depth than previously. As a result, the UK has significant experience in counter-terrorism strategy and serves as a good case study for understanding how a country can respond to a terrorist threat [6]. The UK approach has been largely focused on 'operational' issues such as identification of suspect packages, developing effective search strategies to ensure nothing is left in rolling stock overnight, and contingency planning for evacuation. System design issues have covered such things as avoiding areas in which a bomb or other device could be concealed, control of road vehicle access to stations, and assessment or modification of glazing to control flying debris in the event of a blast.

Countries such as France and Spain have developed strategies individually, based on their own experience and their tolerance of the possible measures, i.e. the acceptability of the measures. For example, prevention of concealment of a bomb through removing litter bins has been conducted extensively in the UK, whereas this was thought unacceptable for most situations in Spain due to inconvenience for passengers, and unacceptable in the USA due to increased littering (which also increased fire risks). Conversely, in Japan the removal of bins led to an overall decrease in litter, as passengers took it home with them [7].

2.3 Transfer of approaches from other modes

In addition to considering international experience, approaches taken for the built environment and by other transport modes, particularly air travel, are in some cases transferable to the rail system. In most cases it is the methods and principles involved in preventing terrorism which are transferrable, while the exact solutions are site or mode specific, and require adaptation to transfer between modes.

The most significant measure that has been transferred from airline practise is the screening of passengers and luggage [8], and some limited screening programs have been put permanently in place, for example on international services to and from London, or deployed at time of elevated threat levels. There are several different scanning technologies emerging for security staff to screen passengers and baggage, although simple manual bag searches are also still common. London Underground have found that sniffer dogs are the most effective for detection of explosives [9], as most technological measures still require further development to be suitable for the rail system environment [10]. The sheer number of people using rail transport every day means that screening every passenger is not realistic or possible without drastically changing passenger experience [11]; the only practical way is to scan a proportion of passengers. These are generally selected at random since profiling (i.e. selecting) by baggage type or behaviour is very difficult to do effectively, given that ‘suspicious behaviour’ is very subjective and there are many factors that may influence it. In addition, profiling can be subject to bias and inaccuracy through pre-conceptions about the visual appearance of terrorists.

A factor that differentiates rail from air transport is its ‘open access’ nature meaning that a perimeter security approach is not suitable for most rail systems [12], limiting the usefulness of searches. Outside stations the track is generally easily accessible, and there are many small and low volume stations, which by the very nature of the system are connected directly into major stations. However screening at random locations complicates planning for terrorists, and can act as a deterrent, even if it cannot intercept all attacks.

2.4 New research directions

Counter-terrorist strategies have generally evolved over time, primarily in response to attacks, although more recently preventative forward planning has been developed as well. This research led approach as been brought about particularly through European level research in projects such as MODSAFE (European Urban Guided Transport sector), RAILPROTECT (Innovative Technologies for Safer and more Secure Land Mass-Transport Infrastructure under Terrorist Attacks, [13]), DEMASST (Demonstration for mass transportation security, [14]) and COUNTERACT (Cluster Of User Networks in Transport and Energy Relating to Anti-terrorist ACTivities, [15]). The 'designing-in' of resilience to attack is one area where there is significant scope for development in the engineering field, and this is considered further in Section 3. Possible routes to quantify the effectiveness of integrating security measures are considered further in Section 5, which looks at risk management as a framework for analysing the cost effectiveness of counter terrorism measures. The overlap with other issues such as counter-crime strategies and fire safety is considered, on the basis that 'dual-use' measures are more likely to be implemented than ones solely targeting resilience to terrorist attack. Other areas in which research is taking place include scanning and detection technology [16], a greater understanding of possible CBRN attacks and in-transit security of hazardous goods [17], intelligent CCTV monitoring [18] (discussed further below), crowd dynamics, behavioural analysis and other psychological approaches to identifying and stopping terrorist activity [19][20].

3 Drivers for 'designing-in' resilience

3.1 Acceptability

An important consideration for the implementation of resilient design is the acceptability of the measures adopted. 'Acceptability' cannot be easily defined as different people have a range of views and perceptions about what is acceptable depending on their role (manager, security personnel, passenger or otherwise) and personal judgements [21]. These views can often change over time in response to other influences such as subsequent attacks locally or worldwide, or to long periods of stability. Different countries have also historically had different standards as to what is acceptable in the mitigation of terrorist attack risk.

In general, anything that adversely affects the smooth running of the rail system, quality of passenger experience (and in consequence its running costs or profitability) will be viewed as undesirable, although this will always have to be balanced with the improvement of security achieved and its proportionality to the assessed risk. Despite being a key vulnerability, moving large numbers of people quickly and easily is a fundamental concept of mass transport [6] and security measures that cause significant delays or constrictions to the flow of passengers would be unacceptable under most circumstances [9]. Similarly, the benefits of designing-in enhanced security measures in the construction or renovation of rail systems must be judged relative to the costs and the security risks present. Section 5 discusses the judgement of proportionality and effectiveness in more depth.

A more subtle part of acceptability is the effect of counter-terrorism measures on aesthetics, atmosphere, perceptions of security and other psychological issues affecting staff and passengers. Highly visible (or even oppressive) counter-terrorism security measures might increase security, but can also promote a climate of fear among passengers, as with some of the reactions to the ‘ring of steel’ created in the City of London in response to IRA bombings [22]. Operators keen to improve security without these problems often opt for passive counter-terror measures whose design can be disguised, hence there is little public perception that the measures are even there, let alone that they have a negative impact on the aesthetics or atmosphere of the transport system. For example trees, large planters and other decoration can be used in preference to barricades to prevent vehicles (and therefore vehicle borne bombs) approaching critical buildings [23]. However, immediately after a recent attack, people may be reassured by highly visible security measures, and this psychological boost or support can be valuable in restoring confidence and normal operation even it if is not necessarily effective at mitigating terrorist threats [24].

3.2 Human factors affecting design

In the event of an emergency, the safe evacuation of all passengers and staff still at risk is a high priority to prevent further casualties. During evacuation the provision of information and guidance can greatly help passengers who may be injured, are in an unfamiliar situation, and have no overview of what has happened or what the best action is. Moreover, unnecessary evacuations caused by false alarms bring inherent risks and costs for large and complex systems such as rail; disturbing the normal operation gives rise to potential risks, as the smoothest and safest operating method ceases [25]. Using crowd dynamics research [26] there is an opportunity for stations and vehicles to be designed for better performance in the event of an evacuation, including identifying what information should be given, and how and where to assist passengers.

Attempting to identify an attack in advance rather than just responding to it, for example through identification of 'suspicious behaviour', has many difficulties [18][27] and there is currently little guidance. One area of research that is addressing this problem is 'intelligent' CCTV that extends human monitoring. For CCTV systems with many cameras (such as those covering an entire light rail network or large station), it has become impossible to fully monitor all the cameras all of the time, as the number of human operators and resources required would be prohibitive. There are also issues of staff attention span and what can be reasonably expected when processing large amounts of visual data. This dramatically reduces the effectiveness of such a system; in many cases they are currently used only to identify details long after an event rather than to support a pre-emptive or reactive response [28]. New developments in CCTV are focussing on the use of software to detect anything unusual and bring it to the attention of security staff [29]. In a rail context, such systems are aiming to detect people moving about in restricted areas, packages left unattended on platforms or on station concourses, the spread of smoke, or even flows of people significantly different to normal operation, for example someone on a platform but not boarding a train for an unreasonable amount of time. Communication of this information between control rooms, security personnel, drivers and passenger alarm points at any time (even within tunnels, or if parts of the system are damaged) is vital for a real-time response to events, however, such extensive monitoring raises issues of public acceptability, privacy and data protection [30].

4 Bomb damage mitigation

Section 2.1 describes that conventional bombings have remained over a long period the most common terrorist attack on rail systems. To support implementing practical solutions for increased resilience this section describes what happens in an engineering sense during a bomb explosion, and links this with effects such explosions would have on rail systems.

4.1 Explosion dynamics

Much of the published research on the effect of explosives is focussed on the threat from vehicle bombs (large improvised explosive devices such as car or truck bombs), and on strategies and guidelines for mitigating this threat, for example by increasing the stand-off between roads and buildings. There is significantly less research in the public domain or academic literature covering explosives detonated within confined spaces such as rail vehicles although work does exist on aircraft structures [31][32]. Given the magnitude of typical blasts it is unlikely that the effects of these explosions can be totally mitigated and the vehicles made 'bomb-proof' within the constraints of weight, cost and available materials. However, design elements can be incorporated to reduce the damage and consequences of an explosion [33]. Incendiary devices are a somewhat different threat, and a consequence of stringent fire standards and good staff training (in response to accidental fires unrelated to terrorism) is that previous attacks have been relatively contained. There is also the threat of a fire as a secondary consequence of an explosion however.

A high explosive blast results from the rapid decomposition of the explosive material into gases which reach high temperature and pressure and subsequently expand rapidly. It is characterised by 2 aspects: a high pressure supersonic shockwave ("blast wave") and a bulk movement of air ("blast wind"). Most of the energy of the blast is contained in the compressed air blast wave (this air previously occupied the explosion site) moving ahead of the expanding gas. As this gas expands its pressure and temperature drop, which together with the momentum of the gas away from the explosion site leads to sub-atmospheric pressure at that site [34]. This causes a reversal of air flow to restore equilibrium, as shown in Figure 3. Air will flow rapidly from areas of high pressure to low pressure, resulting in a bulk movement of air, producing the blast wind. Together, the blast wave and blast wind cause damage in different ways, hence different objects and structures will respond differently although usually one mechanism will dominate. These effects will determine the design requirements for mitigating the effects of a blast.

Diffraction loading by the blast wave (rapid application of pressure on all or many sides of objects as a blast wave passes them) tends to cause brittle materials (e.g. glass, concrete) to shatter and crushes ductile materials (e.g. metals). Some flexible structures tend not to be damaged by diffraction loading, but may be torn apart by drag loading from the blast wind. Objects not rigidly fixed can be set in motion by the blast wind, including people and debris/fragments produced moments earlier by the crushing pressure of the blast wave [35]. The duration of a blast is an important factor when considering the impulse (hence change in momentum) that acts on people and structures. Relative magnitudes and values for the blast wave overpressure are of the order of 170kPa acting for just tens of milliseconds, while the blast wind will be of lower pressure (order of 20kPa) but acts for longer, and reverses direction as the explosion progresses [35]. A blast wave overpressure of this magnitude is sufficient to cause injury but not death [36]; however there is also likely to be a significant chance of injury or death due to the resulting displacement of the body and its collision with the surroundings, in the case of a rail vehicle this might be objects such as seats, hand rails and the vehicle body (see Section 4.3). Furthermore, where a vehicle in motion is severely damaged by an explosion, there may be further damage as the vehicle leaves the rails and/or breaks up.

There are further issues concerning explosions in confined spaces such as rail vehicles, rather than in open air, which also require consideration. Blast waves exhibit wave behaviour of reflection from walls or objects, and diffraction round obstacles. There are also phenomena unique to blast waves, such as Mach stem formation, in which reflected blast waves from an explosion near a surface such as the ground interfere constructively with the incident blast wave to almost double the amplitude (see Figure 4). For cases in which there are multiple reflecting surfaces in close proximity, such within a rail vehicle, the interference of blast waves will be very complex. Different areas within a vehicle will be exposed to significantly different pressures, potentially higher in some regions further from the blast than others close by. Interaction of the pressure wave with objects such as seats and passengers within the vehicle make it difficult to predict blast wave behaviour. In addition to blast wave reflection, an explosion in a confined space will lead to a build-up of pressure, referred to as "gas pressure loading" [37]. Research on buildings has shown that venting (e.g. via windows blowing out) may prevent the build-up of damaging gas pressure, but it offers little protection for people subject to reflecting blast waves within the structure. Depending on proximity to the explosion the timescale for release of pressure through the windows can exceed the time taken for health damage from the blast (see Figure 5). There has been limited research with some experiments for the aircraft industry after the Lockerbie bombing [38], and there are some computational models; however blast wave propagation phenomena within vehicles remain a subject of current research [39]. Where an explosion takes place in a tunnel, the space is further confined and hence the blast is concentrated further, with significantly more damage as a result.

4.2 Fragmentation damage

As well as the blast wave itself, fragmentation of materials and shrapnel are a very significant cause of injury, generally accounting for many more casualties than the blast wave [40]. Fragmentation of materials is usually produced by the crushing blast wave stage of an explosion, and the fragments then move with the blast wind. Fragments are more dangerous than the airflows which produce them because they dissipate their energy over much larger distances than the blast wave; hence they can cause damage at much greater range. For example, the lethal range (i.e. 50% probability of death from the explosion) of a fragmentation grenade is approximately 5m [35]; whereas the lethal range of the blast wave only, from the same quantity of explosive, is approximately 0.75m [36]. Many terrorist bombs contain nails, screws, ball bearings or other such items intended to cause more casualties, for example the bombs used in the Madrid bombings had around 1kg of nails packed around the explosive charge [41]. In a rail transport context, other secondary fragments can include luggage and pieces of the vehicle damaged by the blast wave forming glass or metal shards, which are then set in motion by the blast wind. The use of synthetic films bonded to large areas of glass offers the opportunity to reduce flying debris [42] although the thickness required usually exceeds that of films applied for graffiti prevention.

4.3 Explosion injuries

Injuries caused by explosions can be divided into four categories [43]:

- Primary – due to the effect of the high pressure wave
- Secondary – due to flying fragments or shrapnel
- Tertiary – due to the effects of blast wind
- Quaternary – other mechanisms such as burns

Primary blast injuries are due to the interaction of the high pressure wave with the body, hence gas filled structures are most affected. The ear is most vulnerable to this damage, with perforated eardrums the most common primary blast injury [44]. Blast injury to the lungs is more serious and potentially fatal, with the overpressure causing extensive damage and bleeding to the lung alveoli, leading to respiratory failure [45]. Figure 5 shows the predicted survival rates from primary blast injury of humans exposed to a blast wave [36]. There are other less common, but nonetheless serious injuries – intestinal damage, eye globe rupture and concussion. All of the injuries depend both on the magnitude and duration of the overpressure, and confined space bombings show a much more significant proportion of primary blast injuries than open-air bombings, whereas the other three injury mechanisms have similar proportions in both cases [46]. Confined spaces such as the interior of a vehicle are inherently more dangerous than the open air in a blast situation, and other things being equal the severity of injuries and number of fatalities is likely to be greater.

Although primary blast injuries can be especially significant in confined spaces, secondary blast injuries due to shrapnel or other fragments are the most common cause of injury and death in conventional explosions. As discussed above the distances over which they act are much greater than the primary blast effects. Secondary effects usually result in either penetrating (ballistics) injury or blunt trauma damage, depending on the shape of the fragment objects; the severity of injury will depend on where the object impacts the body and how much kinetic energy it has [44].

Tertiary blast injuries are caused by the blast wind displacing either all or parts of the body, with injuries generally caused by tumbling or impact with a rigid object and the rapid resulting deceleration [45]. This can cause blunt trauma injuries, skeletal fractures, traumatic amputation, or head/brain injury [43]. By definition a confined space has many rigid objects for the body to impact against, for example vehicle walls, seats and handrails. There has been some research [47] into vehicle safety during a crash situation, by redesigning the interior to minimise potential injuries, this could potentially be applied to bomb blast as well. However, the location, direction and magnitude of impacts due to a bomb are unpredictable, making their mitigation more difficult than similar injuries in road or rail accidents, for which the directions of movement and objects involved are more predictable.

There are several different types of injury that fit into the final category; firstly burns due to the high temperature air and heat generated by the explosion. Other potential sources of injury are breathing in dust or toxic by-products of the explosive, or structural collapse of vehicles or buildings leading to crush injury [44].

5 Implementation of counter terrorism security measures in rail system design

When implementing counter-terrorism security measures (and also counter crime measures) there are two broad approaches to consider. One is an ‘active’ approach requiring sustained input from the system operators (with consequent costs). An important example of this type is the provision of security staff for a system and the associated resources required (equipment, communications, control rooms and so forth). The alternative is ‘passive’ measures, for example materials choices, layout and structure of buildings, vehicles or infrastructure. These are environmental features that are either designed-in initially, or sometimes retro-fitted, but typically have low or zero ongoing costs.

Passive measures, in particular for crime prevention, have been developed over the last few decades under the headings of Situational Crime Prevention, or Crime Prevention Through Environmental Design (CPTED) [48]. These are similar techniques, and focus on preventing crime from occurring (rather than punishing offenders when it does) by redesigning the environment to reduce the opportunity for crime. The input to the design process from security experts can help create an environment that makes policing more effective [49], although the mix of policing and urban or rail system design clearly brings questions of acceptability in the case that people feel their environment is being over policed, rather than carefully designed. An example of a rail system with extensive passive crime prevention features is the Météor line on the Paris Métro [50], which includes more transparent materials in station areas, more natural lighting, and spaces with improved sightlines. All these features serve to facilitate surveillance from central command posts.

Opportunities for an engineering input to system design lie in both active and passive areas, for both vehicles and the infrastructure. For example, active technologies include intelligent closed circuit TV systems, and sensing devices capable of explosives detection. Passive approaches include the selection of materials capable of mitigating fragmentation and other hazards in a blast situation, or resisting fire. Wherever design changes are made the existing requirements of the system also need to be met, creating a complex design decision process. For example, in vehicle design there are standards covering crashworthiness, fire resistance, evacuation and disabled access requirements. In design of the built environment of stations there is often the additional issue that several companies may be involved in the ownership, maintenance and operation of the station (e.g. infrastructure owners, rail operators, station shops, cafes and so on). Designing for resilience can therefore be a highly site-specific task, and developing guidelines to best practise remains a current research issue [51].

Considering vehicles, one route to design for better security performance is through developing national and international guidelines (as opposed to standards), possibly using formats similar to European standard EN 45545 for fire safety [52] and BS EN 12663 for rail vehicle crashworthiness [53]. For older vehicles there are opportunities to retro-fit resilient features at major re-fits during the life of the vehicles, and indeed the changing nature of terror threats means that some degree of retro-fit mid-life could be helpful in itself, although it is likely that introduction of measures at the design stage will be more cost effective than retrofitting existing vehicles. The timescales over which guidelines are developed could however be problematic for both new build and retro-fit cases. For vehicle crash-worthiness, even after the underlying engineering for increased safety was developed (which took many years) it took around 10 years more to produce agreed documentation. In the case of terrorist threats, the nature of threat could change considerably over such a long period.

While considering terrorism security issues, it is important to remember that events such as sabotage and arson occur far more regularly as railway crime than as specific terrorist acts. For example, between April 2006 and March 2007 on British railways alone there were 238 recorded cases of arson and over 10,000 counts of criminal damage [54]. According to London Underground security officials: "A business case for measures that are solely associated with terrorism can be hard to build whereas a case that is part of a wider crime reduction strategy and has clear benefits for customers and staff is easier to make – and your terrorism risk benefits can come at no cost" [9]. This is echoed internationally – increased security can reduce the risks and costs of both terrorism and conventional crime [7]. Similarly, measures which aim to reduce regular crime, especially in urban transport, can help deter terrorist attacks through making more obvious 'abnormal' situations such as abandoned packages or unauthorised access to the rail system. However, caution must be exercised as in some cases there can be potential conflict between counter-crime and counter-terrorism strategies [25], and also, the motivations and attitude to being caught can differ greatly between perpetrators of general crime and terrorism, changing the strategies needed. For example, large glazed areas that offer increased visibility can help deter crime, but can be more vulnerable to damage from a bomb attack. In this case, the materials and installation must be carefully considered to minimise this vulnerability while maintaining the security benefits.

5.1 Assessment of effectiveness

The resources for 'designing-in' security measures are necessarily limited, and many other issues (for example coping with extreme weather events) also require attention, so any solution that can address multiple issues is clearly to be favoured. One approach to prioritising investment in resilience and security is therefore to allocate resources based on the predicted cost effectiveness of the measures [1]. Terrorist events are (fortunately) of very low frequency compared to fires or floods, and given the complexity of rail systems different types of attack at different locations will have little in common. Assessment of risk therefore necessitates skilled individual assessment, rather than a simple score or measure of the resilience of a system to attack [55]. Quantitative risk management provides a possible framework to analyse cost effectiveness, and hence prioritise the available resilience options, their benefits and costs. Its first stage is to assess the risk for which comprehensive assessment models specific to transport have been developed [15], but which for generic terrorism risk has been defined as follows [56]:

Risk = threat × vulnerability × consequence

Here, *threat* is defined as the probability that a specific target is attacked in a specific way during a specified period. *Vulnerability* is defined as the probability that damages occur, given a specific attack type, at a specific time, on a given target. Essentially this is the probability that an attack will succeed once initiated. *Consequence* is defined as the expected magnitude of damage, given a specific attack type, at a specific time and target. Risk can be measured in terms of economic costs, injuries, fatalities or physical damages.

This approach has two advantages – firstly it allows quantitative comparison between different types of attack to different parts of a system; secondly it provides a clear mapping between risk and the approaches for mitigating the risks. For example, increased surveillance and detection will reduce the vulnerability of a system, whereas resilient design of the system, increasing preparedness or training for emergencies can help reduce the consequences. However, there is a problem with the analysis in that all of the assessments of threat and measures of the consequences are only estimates, however skilled the assessor. As these estimates will vary between individual assessors there is a major problem in comparison of risk across multiple sites which are assessed by different people, or which have grossly different risk profiles.

Threat probability is essentially based only on intelligence and analysis of patterns in past attacks, and is hence likely to have large potential for error. Vulnerability can be based on more rigorous procedures and an understanding of the security systems in place, so can be less subject to variation for the threats assessed. Consequences of an attack can be analysed by engineering methods such as modelling the potential for structural collapse, or fragmentation of materials during an explosion. However, there are many more variables to consider dependant on the physical situation at the target area, and its assessment still has great uncertainty. A further problem is how to value the different types of consequences relative to one another. For example, if economic loss is used as a common factor to compare attacks, then an economic value corresponding to fatalities, delays and system closures resulting from an attack must be developed. This has been done in the UK for assessing the cost effectiveness of rail safely and vehicle crash-worthiness leading to a figure of around £1.7 million per life saved as the Value of Preventing a Fatality (VPF, 2009 figure [57]), but it requires further research to determine if this figure translates to security cases for which rare but very high consequence events are considered, especially considering people's reactions to terrorism rather than conventional crime (as discussed in Section 1)

An important case in which putting costs on the security benefits would not be required is that of zero cost solutions, i.e. simple changes of design, layout or materials selection which produce benefits such as a reduction of fragmentation during a blast at no additional cost relative to conventional design or materials choices.

5.2 Guidance on risk mitigation

The ALARP (As Low As Reasonably Practicable) principle can be used to guide decisions on the acceptability of risk and risk mitigation [58] however, there may be difficulties in assessing very low probability but high consequence events. Assessment can also be made using the more technical approach of Safety Integrity Levels (SIL) [59], through assessment of different ways by which a certain level of risk reduction and SIL may be achieved. Using the ALARP method the risks are divided into three categories (with the boundaries derived from UK Health & Safety Executive guidance, in terms of likely casualties per year), and dealt with in three ways:

1. The negligible/broadly acceptable region, where no risk reduction is necessary, however the risks should still be monitored and documented to ensure they do not move outside of this region.
2. The tolerable (or ALARP) region, where mitigation measures to move the risk towards the negligible region should be subject to cost-effectiveness analysis.
3. The intolerable/unacceptable region, where risk mitigation must be undertaken, or the activity considered must be stopped.

Figure 6 shows how these regions can be plotted on axes of accident frequency and severity.

To measure cost effectiveness using this approach, new estimates of threat, vulnerability and consequences are made assuming security measures have been implemented. A range of scenarios can be tested, and if the revised consequences for each are analysed in purely economic terms then the reduced risk can be directly compared with the cost of the measures thereby identifying the most cost effective solutions. However, as previously noted, there are likely to be large inaccuracies in the estimates of threat, vulnerability and consequence when considering terrorism events. This is especially the case for very low probability – high consequence events such as a chemical, biological, radiological or nuclear (CBRN) attacks for which alternative assessment procedures may be appropriate [60]. As with the VPF figure highlighted above, the boundaries set for classifying the risk may need to be set differently to other incidents when dealing with terrorism.

6 Conclusions

'Designing-in' resilience involves taking account of potential terrorist attacks at the design stage, to create an environment that inherently reduces the likelihood and consequences of such an event. The purpose of this paper has been to illustrate the process and thinking behind research to inform the development of 'designed-in' resilience, rather than to describe specific measures in detail. Examples of the measures which might be designed-in include glazing to resist blast, or to retain glass fragments, landscaping to prevent unauthorised vehicle access, and removal of structural features which may exacerbate the effects of an explosion. Data on past attacks shows that conventional bombings targeting passenger trains or station platforms (both of which can be defined as 'crowded places') pose the greatest risk to rail systems in terms of casualties. There is generally a good correlation between casualties and overall impact of an attack; exceptions to this being the destruction of key infrastructure. CBRN attacks have been the rarest but could potentially have very serious consequences; they have not been considered in this paper, which has focused on the more common attack types seen previously. Finally, it should be noted that terrorism in the UK is still a very rare event compared with railway crime, however, fear of terrorism can amplify people's perception of the threat and their reaction to its occurrence.

The UK provides an excellent case study of the development of terrorism security strategy for transport, tested during the sustained IRA campaign in the late 20th century, and developed following experience of the mass casualty attack on London on 7th July 2005. There are several areas of ongoing research; this paper considers some of the issues surrounding 'designing-in' resilience, while other areas include scanning and detection technology, intelligent CCTV monitoring and design of stations and vehicles using crowd dynamics research.

Increasing resilience through designing-in security measures offers an opportunity to reduce the vulnerability of the system (for example by making policing more effective), or reduce the consequences of an attack through mitigation of bomb damage, safe evacuation to prevent further casualties, and rapid return to normal operation. Other factors, such as acceptability of counter terrorist measures to the public, system staff and owners, reduction of threat, and cost-effectiveness must be taken into consideration during the development and implementation of particular counter-terrorist measures.

To provide a route for assessing the benefits of designing-in resilience, to assess its cost effectiveness and prioritise investment, further research is needed into technical aspects of resilient design (e.g. materials of improved performance), into evaluation methods such as quantified risk assessment, and into how these can be written into standards and guidelines without costly prescription of unnecessary or out-of-proportion security solutions.

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References

[1] **Mueller, J.** The Quixotic Quest For Invulnerability: Assessing The Costs, Benefits, And Probabilities Of Protecting The Homeland"; National Convention of the International Studies Association San Francisco, California, March 26th-29th, 2008

[2] RIBA guidance on designing for counter-terrorism, The Royal Institute of British Architects, London, 2010.

[3] START Global Terrorism Database, U.S. Department of Homeland Security, 2008, http://www.start.umd.edu/data/gtd/

[4] **Pearce, J.** Hundreds missing in Angola train attack, 12th August 2001, http://news.bbc.co.uk/1/hi/world/africa/1487368.stm, retrieved on 17th February 2010

[5] The Commandos Strike at Dawn, Time magazine, 20th June 1977, http://www.time.com/time/magazine/article/0,9171,915035,00.html, retrieved on 17th February 2010

[6] **Jenkins, B., Gersten, L.** Protecting Public Surface Transportation Against Terrorism and Serious Crime: Continuing Research on Best Security Practises, Mineta Transportation Institute, Report 01-07, September 2001

[7] **Taylor B., Loukaitou-Sideris A., Liggett R., Fink C., Wachs M., Cavanagh E., Cherry C., Haas P. J.** Designing and Operating Safe and Secure Transit Systems: Assessing Current Practices in the United States and Abroad, Mineta Transportation Institute, Report 04-05, November 2005

[8] **Jenkins, B., Butterworth, B.** Selective Screening of Rail Passengers, Mineta Transportation Institute, Report 06-07, February 2007

[9] **Gadomski, C., Lewis, M.** Future Partnerships in critical Infrastructure protection, International Conference on Critical Infrastructure Protection, Helsinki, 4th-5th October 2007. (Available from http://www.helsinki.fi/aleksanteri/civpro/thdata/cip.htm)

[10] **Policastro, A.J., Gordon, S. P.** The use of technology in preparing subway systems for chemical/biological terrorism, Proceedings of the 1999 Commuter Rail/Rapid Transit Conference, Toronto, American Public Transportation Association

[11] Light Railway Security – Recommended Good Practise, Transport Security and Contingencies Directorate (TRANSEC), UK Department for Transport, January 2007

[12] The Government's Response to the House of Commons Transport Committee's Preliminary Report on UK Transport Security, Presented to Parliament by the Secretary of State for Transport, January 2006, reference Cm 6736, The Stationary Office, Norwich, UK

[13] **Larcher, M,** Simulations of a Metro Carriage Exposed to an Internal Detonation, Proceedings of the Samtech Users Conference 2009. Liège (Belgium): Samtech, 2009, 1-8

[14] **Eriksson, E. A.**, Briefing for EC/DE workshop: System-of-Systems Demonstration & Experimentation for Mass Transport Security, September 2009, available from http://www.foi.se/FOI/Templates/ProjectPage____7574.aspx

[15] Counteract, Generic Guidelines for Conducting Risk Assessment in Public Transport Networks; COUNTERACT D3a-n; SSP4/2005/TREN/05/FP6/SO7.48891; March 2009, available from www.uitp.org

[16] **Bogue, R.** Terahertz imaging: a report on progress, *Sensor Review*, 2009, **29**(1), 6 – 12

[17] **Healy, M.J.F., Weston, K., Romilly, M., Arbuthnot, K.** A Model to Support CBRN Defence, *Defense & Security Analysis*, 2009, **25**(2), 119 – 135

[18] **Bigdeli, A., Lovell, B., Sanderson, C., Shan, T. and Chen, S.** Vision Processing in Intelligent CCTV for Mass Transport Security, IEEE Workshop on Signal Processing Applications for Public Security and Forensics, 2007, 1-4

[19] **Drury J., Cocking C., Reicher S., Burton A., Schofield D., Hardwick A., Graham D., Langston P.** Cooperation versus competition in a mass emergency evacuation: a new laboratory simulation and a new theoretical model. *Behav Res Methods*, 2009, 41(3), 957-970.

[20] **Porter, S., Brinke, L.** The truth about lies: What works in detecting high-stakes deception?, *Legal and Criminological Psychology*, 2010, **15**(1), 57-75

[21] **Kappia, J.G., Fletcher, D.I., Bosher, L. and Powell, J.P.** The Acceptability of Counter-Terrorism Measures on Urban Mass Transit in the UK, *Urban Transport XV - Urban Transport and the Environment, WIT Transactions on the Built Environment,* 2009, **107**, 627-636.

[22] **Coaffee J.** Terrorism, Risk and the City – The Making of a Contemporary Urban Landscape, Ashgate, Aldershot, UK, 2003

[23] **Owen E.** Tackling Terrorism, New Civil Engineer; 22nd November 2007, http://www.nce.co.uk/tackling-terrorism/294221.article, retrieved 17th February 2010.

[24] **Schneier B.** The Psychology of Security, 18th January 2008, http://www.schneier.com/essay-155.html, retrieved 17th February 2010.

[25] **Appleton, B.** Report of an inquiry into health and safety aspects of stoppages caused by fire and bomb alerts on London Underground, British Rail and other mass transit systems, Health and Safety Executive, UK, 1992, ISBN 0-11-886394-0

[26] **Still, G.K.** Crowd dynamics, PhD Thesis, University of Warwick, August 2000

[27] **Burkeman, O.** Heads in the clouds, The Guardian, Weekend magazine, 1st December 2007,

http://www.guardian.co.uk/lifeandstyle/2007/dec/01/weekend.oliverburkeman, retrieved 17th February 2010.

[28] National CCTV Strategy, Home Office, UK, October 2007, available from http://www.crimereduction.homeoffice.gov.uk/cctv/National CCTV Strategy Oct 2007.pdf

[29] **Seifert, M.** Intelligent Video Monitoring to Improve Efficiency in Railway Security Applications, Presented at Australian Urban Transit Security Conference, 14th-15th November 2005, Melbourne

[30] **Moncrieff, S., Venkatesh, S., West, G.A.W.** Dynamic Privacy in Public Surveillance, *IEEE Computer*, 2009, **42**(9), 22 – 28

[31] **Simmonsa, M.C., Schleyer G.K.** Pulse pressure loading of aircraft structural panels, *Thin-Walled Structures*, 2006, **44**(5), 496-506

[32] **Florek, J.R., Benaroya, H.** Pulse–pressure loading effects on aviation and general engineering structures—review, *Journal of Sound and Vibration*, 2005, **284**(1-2), 421-453

[33] Transit Security Design Considerations, Federal Transit Administration report, FTA-TRI-MA-26-7085-05, DOT-VNTSC-FTA-05-02, November 2004, available from http://transit-safety.fta.dot.gov.

[34] **Mays, G. C., Smith, P. D.** Blast Effects on Buildings: Design of buildings to optimize blast resistance, Thomas Telford Ltd, 40 Marsh Wall, London, 1996, ISBN 0727720309

[35] Introduction to Naval Weapons Engineering, United States Naval Academy, reference ES310, Spring 1998, http://www.fas.org/man/dod-101/navy/docs/es310/syllabus.htm, retrieved 17th February 2010.

[36] **Bowen, L. G., Fletcher, E. R., Richmond, D. R.** Estimate of Man's Tolerance to the Direct Effects of Air Blast, US Defence Atomic Support Agency, October 1968. Available from Lovelace Respiratory Research Institute, http://www.lrri.org/

[37] **Smith, P. D., Rose, T. A.** Blast loading and building robustness, *Progress in Structural Engineering and Materials*, 2002, **4**(2), 2002

[38] Report on the Accident to Boeing 747-121, N739PA at Lockerbie, Dumfriesshire, Scotland on 21 December 1988, UK Air Accidents Investigation Branch, 1990, http://www.aaib.gov.uk/cms_resources/dft_avsafety_pdf_503158.pdf

[39] **Settles, G.S., Keane, B.T., Anderson, B.W. and Gatto J.A.** Shock waves in aviation security and safety, *Shock Waves*, 2003, **12**(4), 267-275

[40] **Lee, C. Y.** Survey of Blast Trauma from Evolving Tactics of Terrorism, Greater New York Hospital Association Briefing on Blast Injury and Mass Casualty Events, 17th October 2005*,* www.gnyha.org/68/File.aspx

[41] Madrid Train Attacks in Depth, BBC News Special Report, last updated 14 February 2007, http://news.bbc.co.uk/1/hi/in_depth/europe/2004/madrid_train_attacks/default.stm, retrieved 17th February 2010.

[42] **Bogosian, D., Avanessian, H.D.** Blunt trauma from blast-induced building debris, Presented at the 31st Explosives Safety Seminar, August 2004, San Antonio, Texas, available from www.kcse.com/pdfs/P-04-01.pdf

[43] Explosions and Blast Injuries: A Primer for Clinicians, US Centers for Disease Control and Prevention, 14th June 2006, www.cdc.gov/masstrauma/preparedness/primer.pdf

[44] **Cooper, G. J., Maynard, R. L., Cross, N. L., Hill, J. F.** Casualties from Terrorist Bombings, *Journal of Trauma*, 1983, **23**(11), 955-67

[45] **Stein, M., Hirshberg, A.** Medical Consequences Of Terrorism - The Conventional Weapon Threat, *Surgical Clinics of North America*, 1999, **79**(6), 1537-52

[46] **Leibovici, D., Gofrit, O.N., Stein, M., Shapira, S.C., Noga, Y., Heruti, R.J., Shemer J.** Blast Injuries: Bus Versus Open-Air Bombings – A Comparative Study of Injuries in Survivors of Open-Air Versus Confined-Space Explosions, *Journal of Trauma - Injury Infection & Critical Care*, 1996, **41**(6), 1030-1035

[47] **Sutton, A.** The development of rail vehicle crashworthiness, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* 2002, **216**(2), 97-108

[48] **Jeffrey, C. R.** Crime Prevention Through Environmental Design, Sage Publications, Beverly Hills, CA, US, 1977.

[49] **Gaylord M. Galliher J.** Riding The Underground Dragon - Crime Control and Public Order on Hong Kong's Mass Transit Railway, *British Journal of Criminology*, 1991, **31**(1), 15-26

[50] **Myher M. Rosso F**. Designing For Security In Météor: A Projected New Métro Line In Paris, *Preventing Mass Transit Crime, Crime Prevention Studies*, 2006, **6**, 199-216

[51] **Coaffee, J., Moore, C., Fletcher, D.I. and Bosher, L.** Resilient design for community safety and terror-resistant cities, *Proceedings of the Institution of Civil Engineers Municipal Engineer*, 2008, **161**(ME2), 103–110.

[52] Railway applications - Fire protection of railway vehicles – Part 1: General, European Committee for Standardization, prEN 45545-1; July 1998. Available from British Standards Institution, www.bsigroup.com

[53] Railway applications - Structural requirements of railway vehicle bodies, British Standard BS EN 12663:2000, July 2000. Available from British Standards Institution, www.bsigroup.com

[54] Statistical Bulletin 2006/07, British Transport Police, http://www.btp.police.uk/pdf/FOI_publications_statisticalbulletin_2006-07.pdf

[55] **Loukaitou-Sideris, A., Taylor, B., Fink, C.** Rail Transit Security in an International Context: Lessons from Four Cities, *Urban Affairs Review*, 2006, **41**(6), 727-748

[56] **Willis, H., Morral, A., Kelly, T., Medby, J.** Estimating Terrorism Risk, RAND Corporation, Report MG-388, 2005

[57] The Value of Preventing a Fatality (VPF), Rail Safety and Standards Board, London, www.rssb.co.uk, July 2009

[58] Engineering Safety Management, Issue 4, Rail Safety and Standards Board, London, 2007, http://www.yellowbook-rail.org.uk/

[59] Functional safety and IEC 61508, IEC/SC65A/WG14 working group, International Electrotechnical Commission, 2005, IEC, Geneva, Switzerland.

[60] **Kunreuther, H., Meyer, R., Van den Bulte, C.** Risk Analysis for Extreme Events: Economic Incentives for Reducing Future Losses, U.S. Department Of Commerce, National Institute of Standards and Technology, Report NIST GCR 04-871; October 2004

Tables

	1998	1999	2000	2001	2002	2003	2004	Total
Arson	0	0	0	0	0	0	0	0
Assault	0	0	0	461	0	0	0	461
Bomb	205	220	126	56	37	292	2307	3243
CBRN	0	0	0	0	unknown	0	0	unknown
Sabotage	0	0	0	0	0	0	0	0
Infrastructure	0	5	0	0	0	0	0	5
Passenger train	134	176	113	443	33	292	2194	3385
Station	28	22	13	74	unknown	0	113	250 +
Track	43	17	0	0	4	0	0	64

Table 1: Worldwide casualties (combined injuries and fatalities) from terrorist attacks, 1998-2004. The one CBRN incident occurred in Venezuela where a Metro station was attacked with teargas; there were no fatalities but an unrecorded number of people had to be treated for injuries. (Source: US Department of Homeland Security START database)

Figure captions

Figure 1. Terrorist events in the period 1998-2004 using data from US Department of Homeland Security START database. (a) Attacks targeting rail transport. (b) All terrorist attacks.

Figure 2. Rail transport terrorist targets in the period 1998-2004.

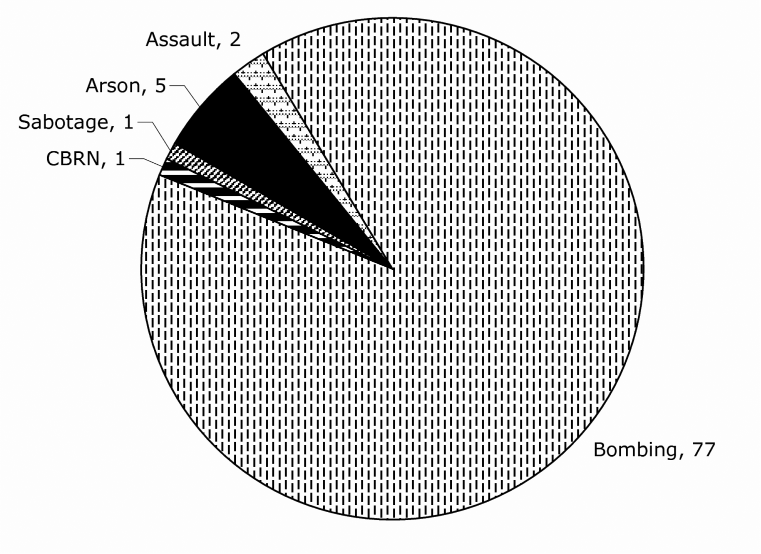
Figure 3. Pressure variation with time for an idealised explosion.

Figure 4. Mach stem formation, in which pressure peaks are formed by positive superposition of the reflected blast wave pressure pulse.

Figure 5. Survival curves for a 70kg man with long axis of body perpendicular to the blast winds in an open air explosion (redrawn from [36]).

Figure 6. Three risk categories illustrating the ‘as low as reasonably practicable’ (ALARP) principle. Risk reduction is possible through mitigating the consequences of an attack (arrow 1), reducing the threat/vulnerability (arrow 2), or a combination of measures (arrow 3).

Figure 1



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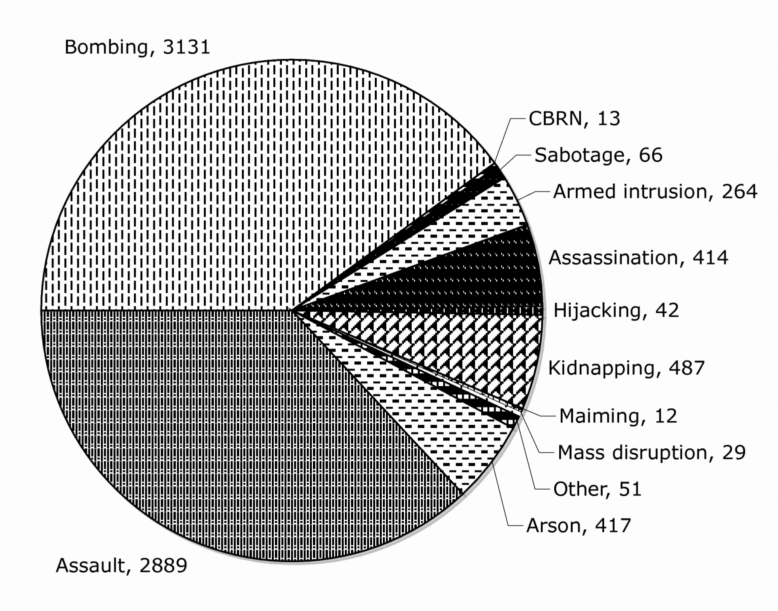

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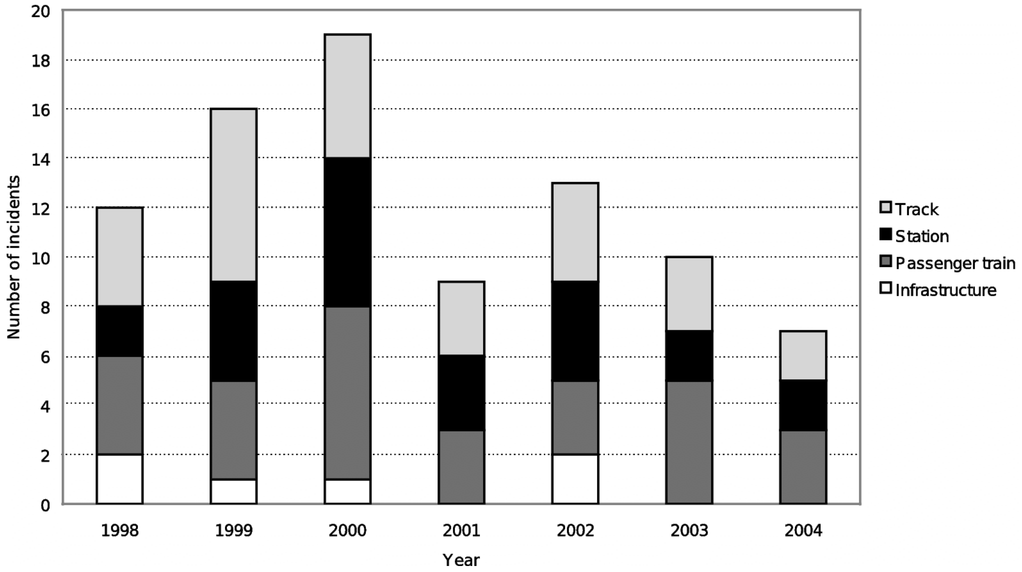

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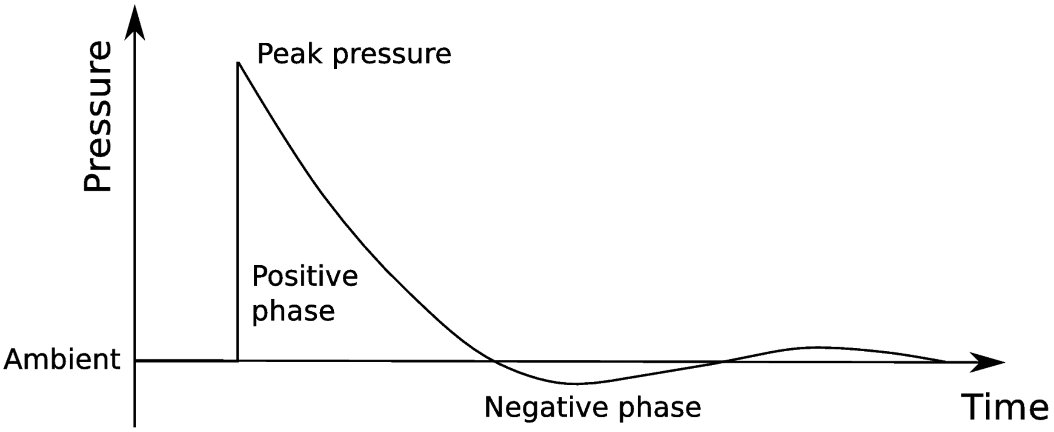

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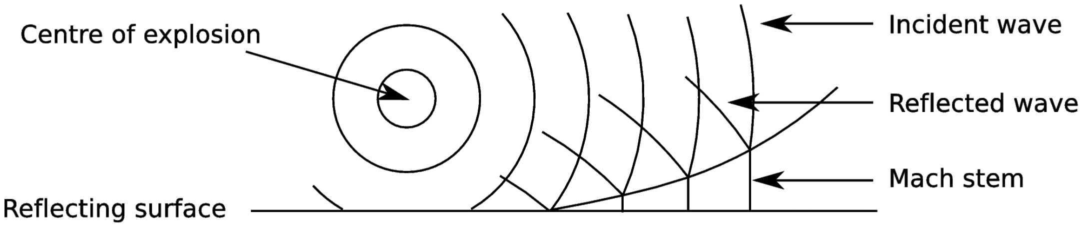

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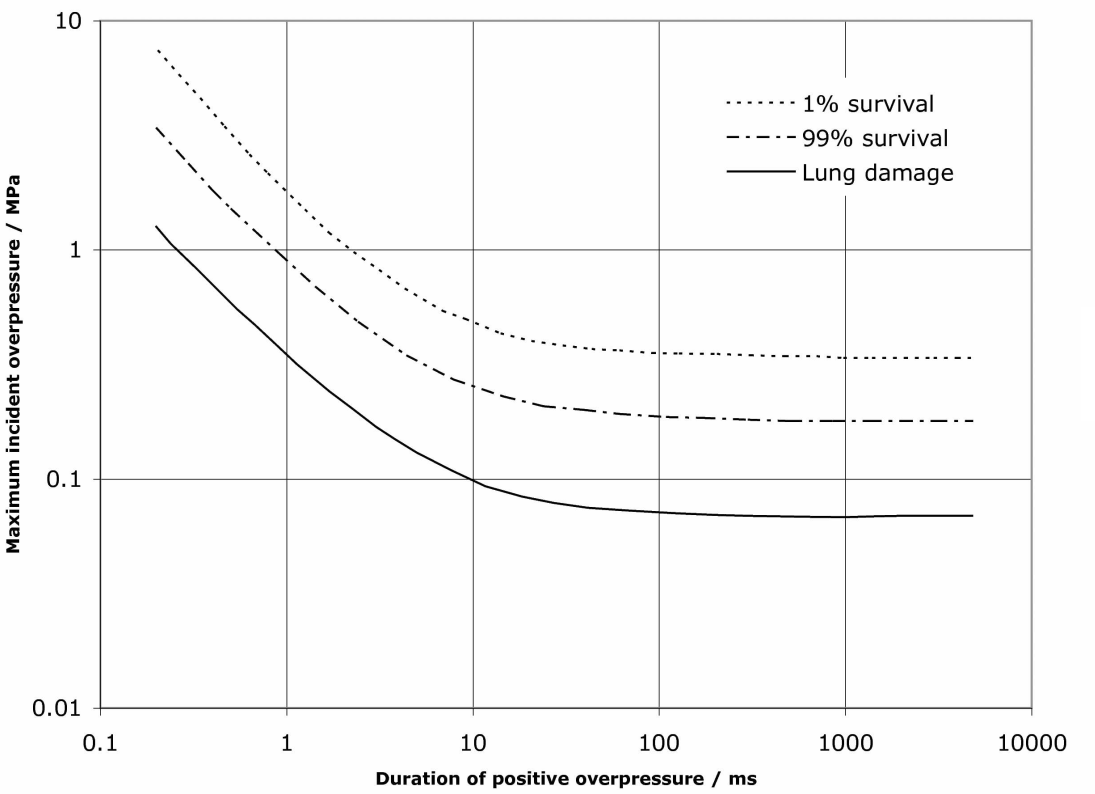

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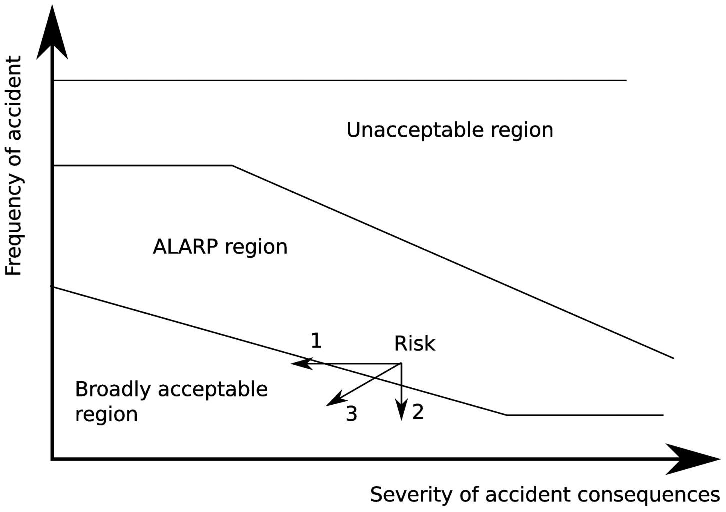

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