Life-safety risks and optimisation of protective measures against terrorist threats to infrastructure

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A decision support analysis considers fatality risks and cost-effectiveness of protective measures, expressed in terms of expected cost spent on risk reduction per life saved for terrorist threats to infrastructure. The analysis is applicable to any item of infrastructure, but in this paper, it is applied to commercial buildings in the US. Risks may be compared with risk acceptance criteria in the form of quantitative safety goals. The risk acceptability and cost-effectiveness of protective measures includes cost of the protective measures, attack probability, reduction in risk due to protective measures, probability of fatality conditional on successful terrorist attack and number of exposed individuals. The risk-based approach developed herein provides a means for initial risk screening based on the broad levels of risk and its acceptability.

Keywords: risk; terrorism; cost-benefit; safety; buildings; decision-making

1. Introduction

Terrorism is a threat that rates very highly in public concerns. This is quite understandable, as communication from government, security services and the media tend to reinforce the perception that this is a ‘high’ or ‘dangerous’ hazard. There is thus a natural trend for decision makers to invest public and private funds in protective measures to counter the threat of terrorism; for example, since 2001 over US$300 billion has been spent by US government agencies on homeland security. It has been argued by some that ‘probably, most of the money and effort expended on counter-terrorism since 2001 has been wasted’ (Mueller 2006). The impact on local, state and national economies of such expenditure can be significant, particularly as most jurisdictions operate in multi-hazard environments, and decisions to invest in risk mitigating measures for one hazard may well come at the expense of other hazards. The present paper addresses this important issue by developing a quantitative risk-based procedure that calculates fatality risks and costs of protective measures arising from terrorist attacks to infrastructure. This allows for the fatality risks and the cost-effectiveness of protective measures to be compared with well-established risk acceptance criteria, thus enabling meaningful decision support about existing risks and under what circumstances (and cost) it is reasonable to invest in risk mitigating (protective) measures.

Risk mitigation to built and other infrastructures that are subject to security and terrorist threats may comprise many possible, and costly, protective measures (e.g. Smith and Hetherington 1994). For example, protective measures may include enhanced perimeter security (vehicle barriers, increased standoff), improved facility design (enhanced ductility and connectivity, strengthened perimeter columns and walls), etc. The cost associated with providing adequate protection to built and other infrastructures can be large; for example, Gould et al. (2006) showed that the structural remediation costs for progressive collapse varied from $2.9 million to $83.3 million for typical large buildings in the US. An issue of interest is whether existing risks are acceptable and is a reduction in risk worth the additional expenditure. The need for a decision-making framework that enables security risks to be quantified in a rational and consistent manner has been widely recognised and decision frameworks for security risk management developed (e.g. FEMA 452 2005). Although a number of decision frameworks exist, a key issue, which is largely unresolved, is the quantification of security risks and effectiveness and costs of mitigating measures. However, the quantification of security risks to assess existing risks and the effectiveness of infrastructure protective measures has been addressed by some researchers (e.g. Stewart et al. 2006, Little 2007, Stewart 2008, Stewart and Netherton 2008). Stewart and Mueller (2008a,b) have conducted
an assessment of increased expenditure on Australian and US air marshal programs and hardening of cockpit doors using similar methodologies where cost-effectiveness is contingent on the likelihood, cost and effectiveness of security/protective measures and consequence of terrorist attacks on infrastructure and society.

A simplified economic analysis by Little (2007) showed that, unless the probability of attack against a specific building is high, the expected benefits are unlikely to offset the cost of protecting multiple structures. Stewart (2008) conducted a preliminary economic decision analysis (risk–cost-benefit analysis) that assessed the cost-effectiveness of protective measures to buildings subject to terrorist attack. The analysis considered consequences in economic terms only (i.e. it did not consider fatality estimates or loss of life valuation). It was concluded that expenditure on risk mitigation measures that exceed a few thousand dollars per year is not cost-effective for commercial buildings in the US subject to non-specific threats. The risks for buildings due to terrorism were shown to be significantly lower than risks due to other (natural) hazards. However, for buildings with significantly higher damage consequences or those facing a specific threat (such as key governmental and international institutions, monumental or iconic buildings or critical facilities), it was shown that it is often cost-effective to implement protective measures. While an assessment of economic (monetary) consequences is important, of more concern to society, as it is with most other low probability–high consequence hazards (nuclear power, chemical process plants, etc.), is the potential for terrorism to cause large loss of life. It is the large loss of life that captures the imagination of citizens, contributing to the anxiety and dread often experienced by the public. It follows that life safety is likely to be the main measure of risk and the criterion for assessing cost-effectiveness of protective measures. Hence, the present paper considers: (i) fatality risks and (ii) cost-effectiveness of protective measures expressed in terms of expected cost spent on risk reduction per life saved.

The risk acceptability and cost-effectiveness of protective measures includes cost of the protective measures, attack probability, reduction in risk due to protective measures, probability of fatality conditional on successful terrorist attack and number of exposed individuals. This approach is applicable for all infrastructures, such as buildings, bridges, offshore platforms, dams, pipelines, sewage systems, communication towers, etc., and even to security activities, such as airport security screening or the federal air marshal service. However, in the present paper, risks are quantified for large (often high-rise) commercial buildings in the US, as this item of infrastructure has been subject to recent terrorist attacks. These risks are compared with risk acceptance criteria in the form of quantitative safety goals. The quantitative safety goals described herein provide a reasonably accurate reflection of societal considerations of risk acceptability (e.g. Stewart and Melchers 1997). However, while acceptable risk acceptance criteria can be quantified to consider (in part) acceptable or tolerable risks, it is likely that decisions may also be made (or over-ruled) on political, social, cultural, economic, security or other non-quantifiable grounds. Nonetheless, it is prudent to assess the risks and costs of any potential decision, and to provide such advice to decision makers before a decision is made.

The risk-based approach developed herein provides a convenient means for initial risk screening, based on the broad levels of risk and its acceptability. However, the approach can also be readily modified to include more detailed threat, vulnerability, impact, cost and benefit information that are possible (and desirable) for site- or infrastructure-specific applications.

2. Quantitative safety goals

Risk acceptance criteria are often provided in the form of quantitative safety goals. In the discussion to follow, quantitative safety goals are reviewed for: (i) annual fatality risks and (ii) costs spent to avoid the loss of a statistical life.

2.1. Annual fatality risks

Stewart and Melchers (1997) reviewed the quantitative safety goals used by the US Nuclear Regulatory Commission, Australian and Dutch hazardous industrial development regulators, US environmental carcinogenic exposure regulators and others. These government regulators are concerned with low probability–high consequence system failure, not unlike the terrorist threat to infrastructure. Hence, their quantitative safety goals seem appropriate for the threat of terrorism. The consensus ‘global’ or generic quantitative safety goals obtained for involuntary fatality risk to an individual are thus:

- annual fatality risks higher than $1 \times 10^{-3}$ are deemed unacceptably high;
- annual fatality risks in the range of $1 \times 10^{-3}$ to $1 \times 10^{-6}$ are generally acceptable if the benefits outweigh the risks to provide an economic or social justification of the risk; and
- annual fatality risks smaller than $1 \times 10^{-6}$ are deemed as negligible and further regulation is not warranted.
The global quantitative safety goals suggested by Paté-Cornell (1994), Reid (2000) and others are in general agreement with those shown above. There is public aversion to risks associated with multiple casualties and catastrophic events, hence safety goals for societal risks may be represented in terms of an $F$–$N$ curve, which is a plot of cumulative frequency ($F$) of $N$ or more fatalities versus number of fatalities ($N$). Despite the tradition for using $F$–$N$ diagrams in some industries, it should be noted that these do not provide a consistent means for comparing the risks between different activities (e.g. Faber and Stewart 2003).

### 2.2. Costs spent on risk reduction per life saved

The cost-effectiveness of protective measures is a measure of the avoidability of risks (e.g. Reid 2000). One measure for the cost-effectiveness of risk reduction, which is particularly relevant for life-safety risks, is the cost spent to avoid loss of one statistical life. The value of a statistical life (VSL) in terms of cost per life saved varies considerably; for example, a median of $42,000 to a maximum of over $10 billion (Tengs et al. 1995). Table 1 shows the expenditure per life estimated to be saved (VSL) for specific US government regulations for risk reduction. Table 1 shows that society (as represented by the US government) is prepared to spend more money to prevent death from ‘dread’ type risks, such as exposure to asbestos and arsenic, than it is to prevent death from more mundane activities, such as driving a motor vehicle. This observation shows that the level of risk averseness is often a function of psychological and political aspects of risk perception. While many individuals may be risk averse,

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Year</th>
<th>Agency</th>
<th>Cost per life saved (millions of 1995 $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unvented space heater ban</td>
<td>1980</td>
<td>CPSC</td>
<td>0.1</td>
</tr>
<tr>
<td>Seatbelt/air bag</td>
<td>1984</td>
<td>NHTSA</td>
<td>0.1</td>
</tr>
<tr>
<td>Aircraft cabin fire protection standard</td>
<td>1985</td>
<td>FAA</td>
<td>0.1</td>
</tr>
<tr>
<td>Steering column protection standards</td>
<td>1967</td>
<td>NHTSA</td>
<td>0.1</td>
</tr>
<tr>
<td>Underground construction standards</td>
<td>1989</td>
<td>OSHA</td>
<td>0.1</td>
</tr>
<tr>
<td>Aircraft seat cushion flammability</td>
<td>1984</td>
<td>FAA</td>
<td>0.6</td>
</tr>
<tr>
<td>Trihalomethane in drink water</td>
<td>1979</td>
<td>EPA</td>
<td>0.5</td>
</tr>
<tr>
<td>Alcohol and drug controls</td>
<td>1985</td>
<td>FAA</td>
<td>0.5</td>
</tr>
<tr>
<td>Auto fuel system integrity</td>
<td>1975</td>
<td>NHTSA</td>
<td>0.5</td>
</tr>
<tr>
<td>Aircraft floor emergency lighting</td>
<td>1984</td>
<td>FAA</td>
<td>0.7</td>
</tr>
<tr>
<td>Concrete and masonry construction</td>
<td>1988</td>
<td>OSHA</td>
<td>0.7</td>
</tr>
<tr>
<td>Passive restraints for trucks and buses</td>
<td>1989</td>
<td>NHTSA</td>
<td>0.8</td>
</tr>
<tr>
<td>Auto side impact standards</td>
<td>1990</td>
<td>NHTSA</td>
<td>1.0</td>
</tr>
<tr>
<td>Children’s sleepwear flammability ban</td>
<td>1973</td>
<td>CPSC</td>
<td>1.0</td>
</tr>
<tr>
<td>Auto side-impact standards</td>
<td>1990</td>
<td>NHTSA</td>
<td>1.0</td>
</tr>
<tr>
<td>Metal mine electrical equipment standards</td>
<td>1970</td>
<td>MSHA</td>
<td>1.7</td>
</tr>
<tr>
<td>Trenching and evacuation standards</td>
<td>1989</td>
<td>OSHA</td>
<td>1.8</td>
</tr>
<tr>
<td>Hazard communication standard</td>
<td>1983</td>
<td>OSHA</td>
<td>1.9</td>
</tr>
<tr>
<td>Trucks, buses and MPV side-impact</td>
<td>1989</td>
<td>NHTSA</td>
<td>2.6</td>
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<tr>
<td>Grain dust explosion prevention</td>
<td>1987</td>
<td>OSHA</td>
<td>3.3</td>
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<tr>
<td>Rear lap/shoulder belts for autos</td>
<td>1989</td>
<td>NHTSA</td>
<td>3.8</td>
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<tr>
<td>Stds for radionuclides in uranium mines</td>
<td>1984</td>
<td>EPA</td>
<td>4.1</td>
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<td>Ethylene dibromide in drinking water</td>
<td>1991</td>
<td>EPA</td>
<td>6.8</td>
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<td>Asbestos occupational exposure limit</td>
<td>1972</td>
<td>OSHA</td>
<td>9.9</td>
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<tr>
<td>Benzene occupational exposure limit</td>
<td>1987</td>
<td>OSHA</td>
<td>10.6</td>
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<tr>
<td>Electrical equipment in coal mines</td>
<td>1970</td>
<td>MSHA</td>
<td>11.1</td>
</tr>
<tr>
<td>Arsenic emission standards for glass plants</td>
<td>1986</td>
<td>EPA</td>
<td>16.1</td>
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<tr>
<td>Cover/move uranium mill tailings</td>
<td>1983</td>
<td>EPA</td>
<td>53.6</td>
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<tr>
<td>Acrylonitrile occupational exposure limit</td>
<td>1978</td>
<td>OSHA</td>
<td>61.3</td>
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<tr>
<td>Coke ovens occupational exposure limit</td>
<td>1976</td>
<td>OSHA</td>
<td>75.6</td>
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<tr>
<td>Arsenic occupational exposure limit</td>
<td>1978</td>
<td>OSHA</td>
<td>127.3</td>
</tr>
<tr>
<td>Asbestos ban</td>
<td>1989</td>
<td>EPA</td>
<td>131.8</td>
</tr>
<tr>
<td>1,2-Dechloropropane in drinking water</td>
<td>1991</td>
<td>EPA</td>
<td>777.4</td>
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<tr>
<td>Hazardous waste land disposal ban</td>
<td>1988</td>
<td>EPA</td>
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<tr>
<td>Municipal solid waste landfills</td>
<td>1988</td>
<td>EPA</td>
<td>22,746.8</td>
</tr>
<tr>
<td>Formaldehyde occupational exposure limit</td>
<td>1987</td>
<td>OSHA</td>
<td>102,622.8</td>
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<tr>
<td>Atrazine/alachlor in drinking water</td>
<td>1991</td>
<td>EPA</td>
<td>109,608.5</td>
</tr>
<tr>
<td>Hazardous waste listing for wood-preserving chemicals</td>
<td>1990</td>
<td>EPA</td>
<td>6,785,822.0</td>
</tr>
</tbody>
</table>

Note: 2007 $ are 1.38 times higher than 1995 $.
decision-making bodies (such as governments) need to be risk neutral (i.e. use expected values) and distribute risk reduction funds in a consistent and equitable manner in order to achieve the best outcomes (risk reduction) for society as a whole. Clearly, however, electoral and lobbyist pressure may well circumvent such rationality, as evidenced by the high number of government regulations that require expenditure exceeding tens of millions of dollars to save one statistical life (see Table 1). Furthermore, the lack of coordination and consistency in risk management between federal, state and local agencies also contributes to ‘social investments in life saving that appear haphazard’ (Tengs and Graham 1996). Tengs and Graham (1996) cite the following example of haphazard or inconsistent regulations: ‘To regulate the flammability of children’s clothing we spend $1.5 million per year of life saved, while some 30% of those children live in homes without smoke alarms, an investment that costs about $200,000 per year of life saved.’

The US Office of Management and Budget recommends the use of VSL for benefit assessment for all proposed federal regulations (e.g. Viscusi 2000). Paté-Cornell (1994) suggests that a risk acceptance criterion based on a VSL of $2 million is appropriate for current practice, and the US Department of Transport adopts a figure of $3 million (Viscusi 2000). For most activities, a VSL of $1 to $10 million is a typical quantitative safety goal, as this provides a reasonably accurate reflection of societal considerations of risk acceptability and willingness to pay to save a life. If a decision maker wishes to be particularly risk averse, then a higher VSL may be selected, but this may lead to inequalities in the distribution of risk reduction funds, which will lead to sub-optimal decisions. In the present paper, a VSL of $7.5 million (in 2007 dollars) is adopted as a quantitative safety goal, as such a value is consistent with many studies, as well as values currently used by most US federal agencies (Viscusi 2000). In other words, if the annual cost per life saved exceeds $7.5 million then such risk reduction expenditure is deemed to have failed a cost-benefit analysis and so is not cost-effective. This means that, if a VSL exceeds $7.5 million, then it is more rational to divert the expenditure to reduce the risks for other hazards where the benefits (lives saved) will be higher. The opportunity cost of doing otherwise can be immense, i.e. when we spend resources on regulations that save lives at a higher cost, we forgo the opportunity to spend those same resources on regulations that save lives at lower cost (e.g. Tengs and Graham 1996).

Note that ensuring that a risk satisfies a quantitative safety goal does not, in itself, mean that the risk is acceptable. A quantitative safety goal should be interpreted with some flexibility, as the quantitative safety goal is a ‘goal’ only and other non-probabilistic criteria are also important in judging the overall acceptability of risks (for more details, see Stewart and Melchers 1997, Reid 2000, Melchers 2001).

3. Measures of risk

3.1. Individual annual fatality risk

The well-known formulation for annual risk (loss) for a system exposed to a hazard is:

$$ Pr(L) = \sum_{H} \sum_{DS} \sum_{L} Pr(H)Pr(DS|H)Pr(L|DS), \quad (1) $$

where $Pr(H)$ is the annual probability of hazard occurrence per item of infrastructure, $Pr(DS|H)$ is the conditional probability of a damage state (e.g. safety hazard) given occurrence of the hazard and $Pr(L|DS)$ is the conditional probability of a loss (e.g. damage costs, fatalities) given occurrence of the damage state. The summation signs in Equation (1) refer to the number of possible hazard intensity levels, damage states and losses. If the loss refers to the fatality of an individual, then $Pr(L)$ represents an individual annual fatality risk.

In the present paper, the hazard under consideration is a terrorist threat to infrastructure, and the measure of loss is fatalities. To assess the life safety and cost-effectiveness of a protective measure, risks are compared to the baseline case of no extra protection. For the baseline case of no extra protection, it is assumed that $Pr(H) = p_{attack}$ represents the annual probability of a ‘successful attack’, causing large loss of life safety. This may represent losses resulting from total devastation, where $Pr(DS|H) = 1$ and $Pr(L|DS) = 1$, i.e. everyone in the attacked item of infrastructure is killed. However, this is likely to be overly conservative. For example, Table 2 shows the probability of building occupant fatality given a terrorist attack $Pr(L|H) = Pr(DS|H)Pr(L|DS)$ for recent terrorist attacks on buildings in the US. The probability that an individual in such a building is killed is, in most cases, quite low.

Various protective measures, such as vehicle barriers, increased standoff, enhanced perimeter security, resilient facility design, etc. will result in fatality risk reduction ($R$) that may arise from a combination of reduced likelihood of terrorist attack, damage states, safety hazards and/or people exposed to the safety hazard. To allow for the reduction in fatality
risks arising from protective measures, it follows from Equation (1) that:

$$
Pr(L) = \frac{(100 - R)}{100} Pr(H)Pr(L|H) \\
= \frac{(100 - R)p_{\text{attack}}Pr(L|H)}{100},
$$

(2)

where $R$ is the percentage risk reduction and $Pr(L|H)$ is the probability of occupant fatality given a terrorist attack assuming no protective measures. For example, if risk reduction is $R = 20\%$, then the existing fatality risk is multiplied by $(100 – R)/100 = 0.8$.

### 3.2. Expected cost spent on risk reduction per life saved

Protective measures will reduce fatality risks, with a reduction in expected fatalities of $p_{\text{attack}}Pr(L|H)RN/100$ where $N$ is the number of people exposed to the hazard. It follows that the expected cost spent on risk reduction per statistical life saved ($E_{LS}$) is:

$$
E_{LS} = \frac{100C_R}{p_{\text{attack}}Pr(L|H)RN},
$$

(3)

where $p_{\text{attack}}Pr(L|H)$ is the baseline individual annual fatality risk assuming no protective measures (see §3.1). $C_R$ is the annual cost spent on protective measures for the item of infrastructure and $R$ is the percentage risk reduction as a result of protective measures.

### 4. Results

#### 4.1. Any item of infrastructure

Figure 1 shows the results of using Equation (2) to calculate annual fatality rate $Pr(L)$ as a function of $p_{\text{attack}}, Pr(L|H)$ and $R$. It is apparent that annual attack probabilities less than $10^{-6}$ results in acceptable risks for infrastructure with no protective measures ($R = 0\%$) and maximum loss of life safety ($Pr(L|H) = 1$). However, as risk reduction increases ($R = 95\%$) or loss of life safety reduces ($Pr(L|H) = 0.5$), the fatality risks may be acceptable for higher attack probabilities.

Figure 2 shows the expected cost spent on risk reduction per life saved ($E_{LS}$) obtained from Equation (3) as a function of $C_R$ and $N$, for $R = 95\%$, $Pr(L|H) = 0.5$ and $p_{\text{attack}} = 1 \times 10^{-6}$, $1 \times 10^{-4}$ and $1 \times 10^{-2}$/building/year. If the attack probability is very high ($1 \times 10^{-5}$/building/year), then Figure 2a shows that most combinations of cost of protective measures ($C_R$) and exposed individuals ($N$) result in expected cost spent on risk reduction per life saved being less than the quantitative safety goal of $\$7.5$ million per life saved. However, as the attack probability increases, or the number of expected fatalities reduces, then the cost per life saved increases (see Figure 2b,c).

Clearly, other diagrams can be derived for other combinations of $p_{\text{attack}}, Pr(L|H)$, $R$ and $N$, as deemed appropriate for the item of infrastructure under consideration. For example, the total cost of protective measures $C_R$ can be estimated for any individual building using readily available protective measure cost data, and estimates of $Pr(L|H)$ may be obtained from statistical evaluation of damage databases, probabilistic risk analysis or expert opinion. Figures 1 and 2 or other outcomes from Equations (2)

### Table 2. Probability of occupant fatality for recent US terrorist attacks.

| Building | Fatalities | Building occupants | Probability of occupant fatality $Pr(L|H)$ |
|----------|------------|-------------------|---------------------------------------------|
| World Trade Center (1993) | 6 | 17,550* | 0.0003 |
| Alfred P. Murrah Federal Building (1995) | 163 | 361–850 | 0.19–0.45 |
| World Trade Center (2001) | 2427 | 35,100* | 0.069 |
| Pentagon (2001) | 125 | 16,200* | 0.008 |

*Estimated from average occupant density of 4 people per 100 m.
or (3) can then be used to assess the safety or cost-effectiveness of protective measures for any individual item or grouping of infrastructure.

4.2. US commercial buildings

There are approximately 4.7 million commercial buildings in the US over 92 m² in size (EIA 2003). Approximately 2% of these commercial buildings (108,000) can be categorised as ‘large’ with floor areas greater then 9300 m² (EIA 2003), which would typically be 5 to 20 storeys high (RSMMeans 2006). To be conservative, it is assumed that building protective measures will reduce the likelihood of a successful attack \( p_{\text{attack}} \) and/or extent of safety hazards and fatalities by \( R = 95\% \). It follows from Equation (3)
that a higher reduction in risk (say from 95% to 99.9%) will increase the cost spent on risk reduction per life saved by more than 5.2%, so any value of R exceeding 95% will have little influence on results.

Stewart (2008) has suggested that the annual attack probability \( p_{\text{attack}} \) for all (4.7 million) and large (108,000) US commercial buildings is approximately \( 1.2 \times 10^{-7} \) and \( 5.1 \times 10^{-6} \)/building/year, respectively, for buildings subject to a non-specific threat. These attack probabilities are in broad agreement with the statistics derived by Ellingwood (2007) and Little (2007). These are only order of magnitude estimates of attack probability, which can vary significantly due to the highly transient nature of terrorism, but is indicative of the general risk to commercial buildings in the US, where the threat is non-specific. Ellingwood (2006) suggests that the minimum attack probability may be increased to \( 10^{-4} \)/building/year for high-density occupancies, key governmental and international institutions, monumental or iconic buildings or other critical facilities with a specific threat.

Note that the results to follow focus on risk and safety of building occupants and not on humans exposed to blast/pressure induced trauma (such as pedestrians). In principle, Equations (2) and (3) can be applied to pedestrians, occupants of passing vehicles, etc., where \( \text{Pr}(L|H) \) is likely to be significantly lower than 0.5, as the likelihood of a particular resident of a city being in the vicinity of the target building is remote, even though their vulnerability may be increased.

4.2.1. Annual fatality risks

Table 2 shows that the probability of building occupant fatality given a terrorist attack \( \text{Pr}(L|H) \) is low. For US commercial buildings, a very conservative estimate of \( \text{Pr}(L|H) \) is taken as 0.5, which represents the effect of significant progressive collapse with little time afforded for safe evacuation. Hence, Equation (2) produces \( \text{Pr}(L) = 0.5p_{\text{attack}} \) for US commercial buildings (assuming no protective measures, i.e. \( R = 0\% \)). The individual annual fatality risks for building occupants based on Equation (2) is shown in Figure 3. Hence, the individual annual fatality risks for occupants of all US commercial buildings are only \( 6.0 \times 10^{-8} \) fatalities/year. This risk measure is well below the quantitative safety goal (‘de minimis’ value) of \( 1 \times 10^{-6} \) fatalities/year (see \( \S 2 \)). However, the individual annual fatality risks for occupants of large US commercial buildings increases to \( 2.5 \times 10^{-6} \) fatalities/year. This risk is slightly higher than the ‘de minimis’ value of \( 1 \times 10^{-6} \) fatalities/year, which suggests that, even though this risk is low, there may be situations where risk reduction is appropriate if the

Figure 3. Individual annual fatality for building occupants risk showing quantitative safety goal of \( 1 \times 10^{-6} \) fatalities/year.

4.2.2. Expected cost spent on risk reduction per life saved \( (E_{\text{LS}}) \)

Since \( \text{Pr}(L) = 0.5p_{\text{attack}} \), Equation (3) can then be re-expressed as:

\[
E_{\text{LS}} = \frac{100C_R}{0.5p_{\text{attack}}RN}. \tag{4}
\]

It is now of interest to quantify \( C_R \) and \( N \) for typical US commercial buildings.

A literature review by Stewart (2008) found that the additional costs of protective measures for new building construction would increase building costs from as little as 1–2% to up to 5–10%. However, Glover (2000) states that many practitioners feel that an additional cost of 1–2% is overly optimistic. To retrofit and strengthen existing structures would be considerably more costly than designing-in such protection during the planning phase of a building project. For example, retrofitting existing US Army buildings increased costs by 8% to 24% (Morris et al. 1991). The structural remediation for progressive collapse of 11 large buildings in the US, on average, costs \$442/m² (Gould et al. 2006), which is roughly equivalent to a 30% increase in initial building costs. It is conservatively assumed herein that the minimum cost of protective measures (\( C_R \)) needed for substantial risk reduction for a new building is 2% of the building costs.
If annual costs of risk mitigation are discounted to present values, then the total cost of protective measures over a period of \( T \) years is:

\[
C_{RT} = \sum_{t=1}^{T} \frac{C_R}{(1 + r)^t}
\]  

(5)

where \( r \) is the discount rate. For a service life of 50 years and a discount rate of 3\%, then for new buildings \( C_{RT} = 2\% \) equates to an annualised cost of \( C_R = 0.078\% \). For an existing building, \( C_{RT} \) is assumed to increase to 10\% or an annualised cost of 0.39\%. These costs may well reduce with time, as more effective and efficient protective measures are developed as a result of experience gained from terrorist attacks.

For an average sized large commercial building of 21,800 \( m^2 \) (EIA 2003) with a median unit construction cost of \( $1380/m^2 \), it follows that an average building will cost approximately \( $30 \) million. This means that the minimum annual cost of protective measures needed for substantial risk reduction is \( C_R = 0.078\% \approx $25,000 \) \( pa \) and \( C_R = 0.39\% \approx $120,000 \) \( pa \) for new and existing large commercial buildings in the US, respectively.

The number of people in a building is also highly variable and is influenced by size of building and occupant density. A survey of 100 buildings in the US reveals an average occupant density of 4.0 people per 100 \( m^2 \) (Persily and Gorfin 2004). The same study also shows that occupied floor area is approximately 66\% of gross floor area. For an average size large commercial building of 21,800 \( m^2 \) (EIA 2003), the average number of occupants is thus \( N \approx 600 \) people. Since \( C_R \) and \( N \) are directly proportional to building floor area, then the ratio \( C_R/N \) is independent of floor area, and so Equation (4) shows that the expected cost spent on risk reduction per life saved \( (E_{LS}) \) is also independent of floor area and hence building size.

Figure 4 shows the expected cost spent on risk reduction per life saved \( (E_{LS}) \) as a function of annual attack probability, for risk reduction of \( R = 95\% \), and annual cost of protective measures for a new or existing building of \( C_R = $25,000 \) \( pa \) and \( C_R = $120,000 \) \( pa \), respectively. The expenditure required to save one life is \$730 million and \$17.1 million per life saved for all new commercial buildings subject to a non-specific threat, respectively. For the baseline case of \( C_R = $25,000 \) \( pa \) and \( N = 600 \), an expenditure of \$730 million per life saved for all new commercial buildings is dramatically higher than the value of an acceptable cost per life saved of \$7.5 million and of most government regulations (see Table 1). However, while an expenditure of \$17.1 million per life saved for large new commercial buildings is still likely to be viewed as an unacceptably high level of expenditure on life safety (cf. \$7.5 million), decision makers may be less certain about risk acceptability, as this hazard provokes a risk averse attitude from government and the public. The values of \( E_{LS} \) increase by 400\% for existing structures due to the five-fold increase in expenditure \( (C_R) \) required to provide appropriate risk reduction for existing structures. Hence, it can be suggested that such expenditure on protective measures is not cost-effective for existing commercial buildings subject to a non-specific threat.

If the annual attack probability for a new building is increased to \( 10^{-4}/\text{building/year} \), which might be the minimum attack probability for high-density occupancies, key governmental and international institutions, monumental or iconic buildings or other critical facilities with a specific threat (Ellingwood 2006), then Figure 4 shows that \( E_{LS} \) reduces to \$877,190 per life saved. If the number of people exposed increases to \( N = 2000 \), then Equation (4) shows that \( E_{LS} \) reduces to only \$263,160 per life saved. These expenditures fall well below the safety goal and so are very likely to be viewed as cost-effective by society.

4.3. Discussion

The number of assumptions, which are often made in the absence of firm data, needed to quantify security risks and costs is large. Threat environment and attack probabilities are the main source of uncertainty in the present risk analysis. Some models exist to predict attack probabilities (e.g. Pate-Cornell and GuiKema 2002); however, even though these models rely on
expert judgements from security and other experts, the aleatory uncertainties can still be high. Security risks are also highly transient, in that the threat environment can change significantly due to events within or beyond the US, events that may reveal new sources of vulnerability to infrastructure.

Stewart (2008) considered damage costs and economic aspects in a preliminary economic decision analysis of terrorist threats to built infrastructure. The present paper considers fatality risks as another criterion for decision support. The results of the present paper are in broad agreement with the conclusions of Stewart (2008), i.e. expenditure typically needed to provide substantial protection to buildings is not cost-effective for new and existing commercial buildings subject to a non-specific threat. The economic risks (Stewart 2008) and annual fatality risks derived herein are also very low, and less than many other existing hazards. The decision support provided by economic and life-safety criteria are, in this case, not contradictory.

A number of other metrics can be used to assess and compare costs and benefits, and the methods described herein provides one approach that, over time, can be refined and improved to allow for more meaningful decision support about the acceptability of existing risks and the cost-effectiveness of risk mitigation strategies for the protection of infrastructure against terrorist threats. While quantitative decision support tools hold some appeal to decision makers, they cannot capture the full and diverse range of societal considerations of risk acceptability. Hence, the results of the present paper should be viewed only as an aid to decision support, where decisions about public safety will often require social, economic, cultural, environmental, political and other considerations.

5. Conclusions

This paper has described fatality risks and cost-effectiveness of protective measures, expressed in terms of expected cost spent on risk reduction per statistical life saved for terrorist threats to infrastructure. The decision support analysis can be applied to an individual item or a category of infrastructure in general, and the risks compared with risk acceptance criteria in the form of quantitative safety goals. It was found that the annual fatality risks are very low for small and large commercial buildings in the US without protective measures subject to a non-specific threat. It was also suggested that expenditure typically needed to provide substantial protection to buildings is not cost-effective for new and existing commercial buildings subject to a non-specific threat. However, for a specific threat, the provision of protective measures is more likely to be cost-effective.

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References


