J Transp Secur (2008) 1:143–159
DOI 10.1007/s12198-008-0013-0

A risk and cost-benefit assessment of United States aviation security measures

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Received: 24 April 2008 / Accepted: 29 April 2008 /
Published online: 30 May 2008

Abstract This paper seeks to discover whether aviation security measures are cost-effective by considering their effectiveness, their cost and expected lives saved as a result of such expenditure. An assessment of the Federal Air Marshal Service suggests that the annual cost is $180 million per life saved. This is greatly in excess of the regulatory safety goal (societal willingness to pay to save a life) of $1–$10 million per life saved. As such, the air marshal program fails a cost-benefit analysis. In addition, the opportunity cost of these expenditures is considerable, and it is highly likely that far more lives would have been saved if the money had been invested instead in a wide range of more cost-effective risk mitigation programs. On the other hand, hardening of cockpit doors has an annual cost of only $800,00 per life saved, showing that this is a cost-effective security measure.

Keywords Terrorism · Security · Risk · Cost-benefit analysis · Aviation

Introduction

For many years now the United States Office of Management and Budget (OMB) has recommended the use of cost-benefit assessment for all proposed federal regulations, and such assessments are routinely conducted by the Nuclear Regulatory Commission, the Environmental Protection Agency, the Federal Aviation Administration, and other agencies. In addition, the 9/11 Commission Report called on the

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government to implement security measures that reflect assessment of risks and cost-effectiveness. Yet despite the massive expenditures involved, a senior economist at the Department of Homeland Security recently acknowledged that “We really don't know a whole lot about the overall costs and benefits of homeland security” (Anderson 2006).

Several risk-based approaches to cost-benefit analysis that consider economic and life-safety criteria for the protection of buildings, bridges and other built infrastructure have been developed, with cost-effectiveness contingent on the likelihood, cost, and effectiveness of security/protective measures and consequence of terrorist attacks on such infrastructure (Little 2007; Stewart 2007, 2008). Following this approach, Stewart and Mueller (2008a) conducted an assessment of increased United States federal homeland security expenditure since the 9/11 attacks and of expected lives saved as a result of such expenditure. The cost-benefit analysis suggests that the annual cost per life saved ranges from $64 million to $600 million, greatly in excess of the regulatory safety goal (societal willingness to pay to save a life) of $1–$10 million per life saved. This means that $300 billion spent by the United States government to protect the American homeland from terrorism since 2001 fails a cost-benefit analysis. These findings focus on the total homeland security budget. This is not to say, however, that every specific security measure fails to be cost-effective. There may be some that are. In all cases, a detailed analysis of each security measure that considers their cost and effectiveness with respect to expected lives saved is appropriate and potentially instructive, enabling as it does a meaningful assessment of the merits of each security measure in a rational, consistent, and transparent manner. There is an urgent need for such detailed analyses.

Since 9/11 the United States Transportation Security Administration (TSA) and other government agencies in the United States, Canada, Europe, Australia and elsewhere have devoted much effort and expenditure to attempt to ensure that a 9/11 type attack involving hijacked aircraft is not repeated. In particular, significant expenditure has been dedicated to two aviation security measures aimed at preventing terrorists from hijacking and crashing an aircraft into buildings and other infrastructure:

- Hardened cockpit doors
- Federal Air Marshal Service

These two security measures cost the United States government and the airlines nearly $1 billion per year (CRC 2007). This paper seeks to discover whether these new aviation security measures are cost-effective. The preliminary cost-benefit analysis considers the effectiveness of aviation security measures, their cost and expected lives saved as a result of such expenditure. This will involve a quantitative estimate of risks and benefits, as for policy decisions it is often preferable to communicate risks with numbers rather then words (Mandel 2005). This paper provides a sound starting point for discussion about how to manage aviation security (and other counter-terrorism measures) in an environment where funds are limited and the opportunity costs are high if funds are not shown to maximize life safety.

The adverse effects of terrorism are many, but the two dominant consequences are loss of life/injury and economic (monetary) losses. Experience suggests that property damage, loss of business, and other economic losses as a result of terrorism tend to be short-lived, particularly for developed nations which typically have resilient infrastructure, institutions, and economies. Of more concern to these societies, as with most other low probability/high consequence hazards such as nuclear power and chemical process plants, is the potential for terrorism to cause loss of life. This is what captures the imagination of citizens, contributing to the anxiety and dread they often experience. It follows that life-safety is likely to be the main criterion for assessing cost-effectiveness of aviation security expenditure.

Many uncertainties exist in quantifying risks, particularly for threats such as terrorism where data are scarce or non-existent and where the threat is highly transient. Some sophisticated statistical approaches exist for terrorist threat prediction (Paté-Cornell and Guikema 2002; Plum et al 2004; John and Rosoff 2007), however, even though these models rely on expert judgments from security and other experts, the inherent uncertainties can still be great. Hence, since the present paper will rely on judgment and scenario analysis to quantify key risk parameters, the outcomes will be subject to a sensitivity analysis to assess if cost-benefit conclusions are influenced by the acknowledged uncertainty in risk reduction and other parameter estimates.

Regulatory safety goal: societal willingness to pay to save a life

While risks are seldom acceptable, they are often tolerable (or accepted reluctantly) if the benefits are seen to outweigh the costs. There is a large amount of literature devoted to the problem of how to define what risks are accepted to society, and those which are not, as all activities bear some risk. Activities with large potential for loss of life or severe economic or social consequences, such as nuclear energy, chemical processes, and aviation, have since the 1960s been subject to methodical and quantitative risk assessments (eg Stewart and Melchers 1997). The regulators of potentially hazardous industries and activities such as the NRC, FAA and EPA set risk acceptance criteria based on a cost-benefit analysis. Many risks can be reduced, though at increasing cost. A cost-benefit analysis provides a means to measure the cost associated with avoiding the risk, to determine whether such a cost is excessive, therefore failing to be a productive utilization of society's resources.

The OMB recommends the use of value of a statistical life for benefit assessment for all proposed federal regulations (Viscusi 2000). The cost per life saved varies considerably with the activity or regulation, 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 for specific United States government regulations for risk reduction. As can be seen, society (as represented by the United States government) spends far more money per life saved for efforts to prevent death from 'dread' type risks such as exposure to asbestos and arsenic than for some efforts to prevent death from more mundane activities such as driving a motor vehicle. This is often a function of psychological and political aspects of risk perception (eg. Slovic 2000). While it is recognized that many individuals may be risk averse, decision-making bodies (such as government) need to distribute risk reduction funds in a consistent and equitable manner in order to achieve the best outcomes (risk reduction) for

Table 1 Regulatory expenditure per life saved (adapted from Tengs et al 1995).

Regulation	Year	Agency	Cost per life saved (millions of 1995 dollars)
Unvented space heater ban	1980	CPSC	0.1
Seatbelt/air bag	1984	NHTSA	0.1
Aircraft cabin fire protection standard	1985	FAA	0.1
Steering column protection standards	1967	NHTSA	0.1
Underground construction standards	1989	OSHA	0.1
Aircraft seat cushion flammability	1984	FAA	0.6
Trihalomethane in drink water	1979	EPA	0.5
Alcohol and drug controls	1985	FRA	0.5
Auto fuel system integrity	1975	NHTSA	0.5
Aircraft floor emergency lighting	1984	FAA	0.7
Concrete and masonry construction	1988	OSHA	0.7
Passive restraints for trucks and buses	1989	NHTSA	0.8
Auto side impact standards	1990	NHTSA	1.0
Children's sleepwear flammability ban	1973	CPSC	1.0
Auto side-impact standards	1990	NHTSA	1.0
Metal mine electrical equipment standards	1970	MSHA	1.7
Trenching and evacuation standards	1989	OSHA	1.8
Hazard communication standard	1983	OSHA	1.9
Trucks, buses and MPV side-impact	1989	NHTSA	2.6
Grain dust explosion prevention	1987	OSHA	3.3
Rear lap/shoulder belts for autos	1989	NHTSA	3.8
Standards for radionuclides in uranium mines	1984	EPA	4.1
Ethylene dibromide in drinking water	1991	EPA	6.8
Asbestos occupational exposure limit	1972	OSHA	9.9
Benzene occupational exposure limit	1987	OSHA	10.6
Electrical equipment in coal mines	1970	MSHA	11.1
Arsenic emission standards for glass plants	1986	EPA	16.1
Cover/move uranium mill tailings	1983	EPA	53.6
Acrylonitrate occupational exposure limit	1978	OSHA	61.3
Coke ovens occupational exposure limit	1976	OSHA	75.6
Arsenic occupational exposure limit	1978	OSHA	127.3
Asbestos ban	1989	EPA	131.8
1,2-Dechloropropane in drinking water	1991	EPA	777.4
Hazardous waste land disposal ban	1988	EPA	4,988.7
Municipal solid waste landfills	1988	EPA	22,746.8
Formaldehyde occupational exposure limit	1987	OSHA	102,622.8
Atrazine/alachlor in drinking water	1991	EPA	109,608.5
Hazardous waste listing for wood-preserving chemicals	1990	EPA	6,785,822.0

2007 dollars are 1.38 times higher than 1995 dollars

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 of tens of millions of dollars and more to save one statistical life. Further, the lack of coordination and consistency in risk management between federal, state and local agencies also contributes to haphazard or inconsistent regulation. Tengs and Graham (1996) cite the following example: "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".

Paté-Cornell (1994) suggests that a cost per life saved of $2 million or less is appropriate for current practice, and the United States Department of Transport adopts a figure of $3 million (Viscusi 2000). For most activities a cost per life saved not exceeding $1–$10 million is typical (Viscusi 2000) as this provides a reasonably accurate reflection of societal considerations of risk acceptability and willingness to pay to save a life. In other words, if the annual cost per life saved exceeds $1–$10 million, such risk reduction expenditure is deemed to have failed a cost-benefit analysis and so is not cost-effective. In such cases it is more rational to divert the expenditure to reduce the risks for other hazards where the benefits (lives saved) will be higher.

Cost per life saved is a very robust indicator of societal risk acceptability as it considers costs and benefits in a logical and transparent manner. However, a regulatory safety goal such as this should be interpreted with some flexibility as the regulatory safety goal is a 'goal' only and other non-quantifiable criteria may be important also in judging the overall acceptability of risks (eg. Stewart and Melchers 1997; Reid 2000; Melchers 2001). Past experience shows that it is likely that decisions may be made (or over-ruled) on political, psychological, social, cultural, economic, security or other non-quantifiable grounds. For example, some risks may be deemed unacceptable under any conditions based on morality (Schneier 2006) or based on their symbolic value to society. Some benefits may also be seen as intangible (or indirect) which may make them difficult to be included in a formal quantitative decision-making approach (Prentice 2008). Nonetheless, the cost per life saved is a useful metric for assessing trade-offs, which can provide a starting point for further discussion and perhaps more detailed and complex analysis of how to manage the often conflicting societal preferences associated with assessments of risk, cost and benefits.

Aviation security risk reduction measures

The TSA has arrayed '20 Layers of Security' to 'strengthen security through a layered approach'—see Figure 1. This is designed to provide defense-in-depth protection of the traveling public and of the United States transportation system. Of these 20 layers, 14 are 'pre-boarding security' (i.e., deterrence and apprehension of terrorists prior to boarding aircraft):

1. Intelligence
2. Customs and border protection
3. Joint terrorism task force
4. No-fly list and passenger pre-screening
5. Crew vetting
6. Visible Intermodal Protection Response (VIPR) Teams
7. Canines
8. Behavioral detection officers
9. Travel document checker
10. Checkpoint/transportation security officers
11. Checked baggage
12. Transportation security inspectors

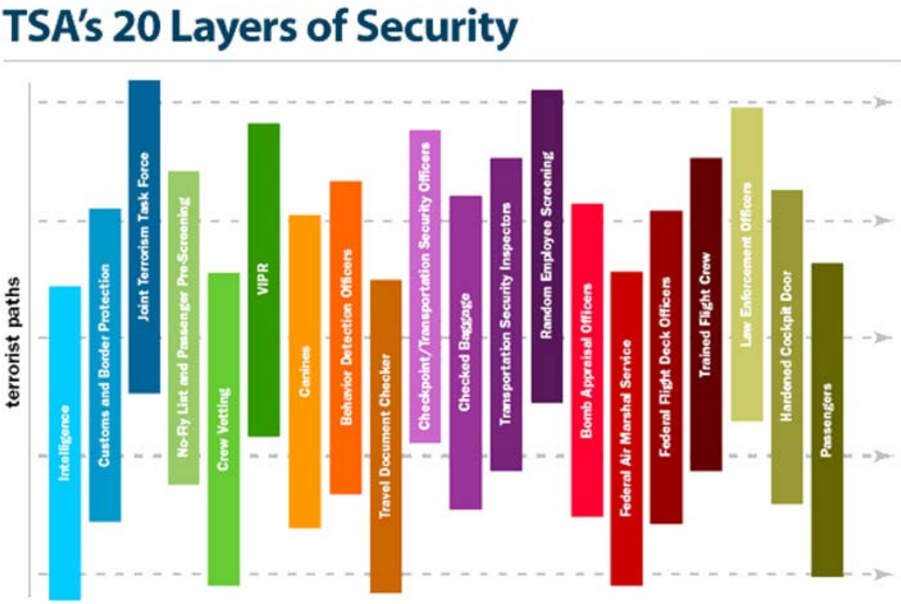

Figure 1 TSA's 20 layers of security

13. Random employee screening
14. Bomb appraisal officers

The remaining six layers of security provide 'in-flight security':

15. Federal Air Marshal Service
16. Federal Flight Deck Officers
17. Trained flight crew
18. Law enforcement officers
19. Hardened cockpit door
20. Passengers

The six in-flight security measures can be grouped broadly as:

- Crew and Passenger Resistance (Federal Flight Deck Officers, Trained Flight Crew, Passengers).
- Hardened Cockpit Door
- Federal Air Marshal Service (including Law Enforcement Officers)

The risk that is the focus of this paper arises from the likelihood and consequences of an aircraft hijacking that could lead to 9/11 type attacks on buildings and other infrastructure. That is, we are concerned with the costs and benefits of measures that seek to prevent exact duplications of 9/11 in which commercial passenger airlines are commandeered, kept under control for some time, and then crashed into specific targets. We do not deal with efforts to prevent other air mishaps like the blowing up of an airliner without hijacking it or attempting to shoot it down with a missile. Such threats cannot be deterred or confidently prevented by hardened cockpit doors or air marshals, and are outside the scope of this cost-benefit analysis.

If pre-boarding security fails, terrorists on board who seek to replicate the events of 9/11 may be foiled by one or more of three security measures. These are now discussed.

Crew and passenger resistance

One reason for the extent of the losses of 9/11 was the reluctance of crew and passengers to confront and resist the hijackers. This is perfectly understandable as most previous hijackings ended peacefully or with minimal loss of life as the main response to a hijacking was to "get the plane on the ground so negotiations can begin" (Schneier 2006). Indeed, only a few months earlier three terrorists had commandeered a Russian airliner, demanding that it be flown to Saudi Arabia at which point they were overcome by local security forces with almost no loss of life (Kramer 2004).

The 9/11 suicide attacks on the World Trade Center and Pentagon changed this perception. Hence, on hearing of these attacks, the crew and passengers on the fourth plane, United Airlines Flight 93, overpowered the hijackers before the aircraft could reach its intended target. Passengers will now fight back if there is any indication that the terrorists' intent is to enter the cockpit or that they are suicidal in any way. As pilot Patrick Smith puts it:

> "We first need to revisit the morning of September 11th, and grasp exactly what it was the 19 hijackers so easily took advantage of. Conventional wisdom says the terrorists exploited a weakness in airport security by smuggling aboard box-cutters. What they actually exploited was a weakness in our mindset—a set of presumptions based on the decades-long track record of hijackings. In years past, a takeover meant hostage negotiations and standoffs; crews were trained in the concept of "passive resistance." All of that changed forever the instant American Airlines Flight 11 collided with the north tower. What weapons the 19 men possessed mattered little; the success of their plan relied fundamentally on the element of surprise. And in this respect, their scheme was all but guaranteed not to fail. For several reasons—particularly the awareness of passengers and crew—just the opposite is true today. Any hijacker would face a planeload of angry and frightened people ready to fight back. Say what you want of terrorists, they cannot afford to waste time and resources on schemes with a high probability of failure. And thus the September 11th template is all but useless to potential hijackers." (Smith 2007; Mueller 2006)

Thus, an attempted hijacking of a Qantas domestic (Australian) flight in May 2003 was foiled by crew and passengers: "Two flight attendants were stabbed and two passengers were injured as they struggled to restrain the armed man, who had attempted to enter the cockpit armed with two wooden stakes, an aerosol can and a lighter" (Murphy and Hudson 2003). Such instances of crew and passenger resistance to attempted hijackings clearly demonstrate the new paradigm that crew and passengers will no longer be passive in the event of a hijacking threat, particularly if the hijacker is suspected to be executing a suicide attack. For this reason, flight crews have shown interest in the Federal Flight Deck Officer (FFDO) program which allows volunteer pilots and crew members to transport and carry firearms to defend the flight deck of aircraft against acts of criminal violence or air piracy. It is estimated that 8% of pilots in the United States are Federal Flight Deck

Officers (Kaye 2007). The FY2007 TSA budget for FFDO and crew training program is $25 million. Passengers, of course, receive no training whatever. That is to say, the single security layer that, according to Smith (2007), is most important for foiling another 9/11 costs nothing at all.

The alertness of crew and passengers may also sometimes disrupt other kinds of terrorist efforts besides hijacking. For example, the 'shoe bomber' on a December 2001 American Airlines flight from Paris to Miami was foiled and apprehended by the prompt action on concerned passengers and crew.

Hardened cockpit doors

The FAA required operators of more than 6,000 planes to install hardened cockpit doors by 9 April 2003 in order to protect cockpits from intrusion and small-arms fire or fragmentation devices. The FAA also required foreign airlines serving the United States to harden their cockpit doors. The FAA mandated that 'The doors will be designed to resist intrusion by a person who attempts to enter using physical force. This includes the door, its means of attachment to the surrounding structure, and the attachment structure to the bulkhead'. It also requires that the cockpit doors remain locked and cockpit access controlled (FAA 2002). The purchase and installation cost of each hardened cockpit door is typically $30,000 to $50,000. The total cost to airlines is estimated as $300–$500 million over a 10-year period, including the cost of increased fuel consumption due to the heavier doors (FAA 2003). This cost will decrease over time as door installation costs for new aircraft will be less than for existing aircraft. While the effectiveness of these doors in restricting cockpit access to a determined hijacker may be questioned (Lott 2004), there is little doubt that hardened cockpit doors will deter and delay a hijackers attempt to enter the cockpit. A best estimate annual cost of hardening cockpit doors is $40 million.

Hardened cockpit doors may be useful in preventing a direct replication of 9/11, but, unlike crew and passenger resistance, they contribute little to the prevention or mitigation of other kinds of terrorist acts on airplanes such as detonation of explosives.

Federal Air Marshal Service

The Federal Air Marshal Service is comprised of approximately 2,500 to 4,000 air marshals (Meckler and Carey 2007). Air marshals are estimated to be on no more than 10% of flights, and by some estimates, on less than 5% of flights (Hudson 2004, 2005). However, Thomas Quinn, director of the Federal Air Marshal Service has dismissed press reports that the agency was covering only 3% to 4% of commercial flights in the United States on a daily basis. Although he declined to give specifics, Quinn said his agents cover "more than 5%" of some 28,000 daily commercial flights in the United States (Meeks 2004). These are often 'high-risk' flights based on intelligence reports (Kearney 2005). The FY2007 budget for the Federal Air Marshal Service is $719 million (CRC 2007). In addition, airlines are expected to provide free seats to air marshals, seats which are generally in first class to allow observation of the cockpit door, and the Air Transport Association estimates that this costs airlines $195 million per year in lost revenue (Poe 2005). A best estimate annual government and airline cost for the Federal Air Marshal Service is $900 million.

Law enforcement officers may be on some flights, mostly due to reasons other than counter-terrorism such as escorting prisoners, VIP personal protection, etc. However, their numbers will not significantly boost the percentage of flights that have an armed air marshal or other law enforcement officer on board. The presence of air marshals or other law enforcement officer is likely to have a deterrent effect, but this is ameliorated by the low percentage of flights that they can cover. It might even be argued that some crew and passengers may be reluctant to be the first to confront a hijacker if they believe an air marshal is on board, a hesitation that could conceivably give attempted hijackers the time they need to execute their plans. Hence, the anticipated presence of air marshals may be counter-productive in some cases. Moreover, air marshals have made 59 arrests since 2001, but none of these incidents has been related to terrorism (Meckler and Carey 2007).

The goal of the air marshals is primarily to prevent a replication of 9/11—a reason for putting them in the first class section upfront. Conceivably, they could be helpful in other terrorist situations—for example, if a passenger tried to blow up the airliner—but their added value over crew and passenger resistance is likely to be rather small.

Annual cost per life saved

Increased expenditure on security is expected to reduce fatality risks. The annual cost per life saved (C_{LS}) is

$$C_{\mathrm{LS}} = \frac{C_{\mathrm{R}}}{\text{lives saved due to enhanced security measures}} \tag{1}$$

where C_R is the annual cost spent on enhanced security measures. The expected number of annual lives saved is the fatality rate before enhanced security measures multiplied by the percentage risk reduction due to enhanced security measures (R), then

$$C_{\mathrm{LS}} = \frac{100 C_R}{R \times \text{fatality rate before enhanced security measures}} \tag{2}$$

The following sections discuss the quantification of key parameters in Eq. (2); namely,

- risk reduction due to enhanced security measures (R)
- annual fatality rate before enhanced security measures

Effectiveness of aviation security measures to prevent a replication of 9/11

The percentage reduction in the risk of a replication of 9/11 due to post-9/11 aviation security measures (R) needs quantification for the following aviation security measures:

- R(pre-boarding security)
- R(crew and passenger resistance)

- R(hardened cockpit door)
- R(Federal Air Marshal Service)

The extra and more vigilant intelligence, immigration and passport control, airport screening, and other pre-boarding security measures implemented since 9/11 as arrayed in the TSA's 14 layers of security should result in an increased likelihood of detection and apprehension of terrorists. Increased public awareness is also of significant benefit to aviation security. Added to this are the much enhanced preventative policing and investigatory efforts that have caught potential terrorists including, in the U.K. in 2006, some planning to blow up airliners. Combined, we suggest, these measure by themselves reduce the risk of a replication of 9/11 by at least 50%, and this is likely to be a lower bound value. There has been no successful hijacking anywhere in the world since 9/11 and very few attempts at blowing up airliners—and none of these in the United States. In consequence, we suspect, R(pre-boarding security) is likely to be much greater than 50%. Nonetheless, for the present analysis assume R(pre-boarding security)=50%.

If there is an attempt to hijack an aircraft, it is assumed all three in-flight security measures have an equal share of risk reduction; namely,

$$R(\text{hardened cockpit door}) = R(\text{crew and passenger resistance}) = R(\text{air marshals}) \quad (3)$$

This is conditional on air marshals being on the aircraft. However, the probability of air marshals being on the hijacked flight is near 5%. On the other hand, air marshals are more likely to be on 'high-risk' flights based on intelligence reports, and it follows that the probability of an air marshal being on a flight is higher if terrorists might also be on the flight. However, experience from Australian air marshals is that "following increases in screening at airports and the installation of bullet-proof cockpit doors, there is little intelligence indicating which flights are at risk", and so now air marshals only "have random assignments or fly to protect VIPs" (Kearney 2005). Nonetheless, to be conservative it is assumed that the probability of air marshals being on a plane is Pr(air marshals on plane)=0.1 to account for their increased likelihood of being present on higher risk flights. Hence:

R(pre-boarding security)	50.0%
R(crew and passenger resistance)	16.67%
R(hardened cockpit door)	16.67%
R(Federal Air Marshal Service) $= R(\text{air marshals}) \times \Pr(\text{air marshals on plane}) = 16.67 \times 0.1$	1.67%

The risk reduction due to the Federal Air Marshal Service is appropriate for hijacking of a single aircraft, or for hijacking of multiple aircraft. If there are air marshals on every flight (and therefore Pr(air marshals on plane)=1.0), if all cockpit doors are hardened, and if crew and passengers will resist a hijacking, the risk reduction is 100%. In other words, every attempted hijacking will be foiled. This is a best case scenario, but there but there may be scenarios under which hijackings can still occur. Schneier (2006) suggests several: "a plane that's empty enough that the hijackers outnumber the passengers, a hijacker who succeeds in convincing the passengers that he's not suicidal or a terrorist (carrying a baby would go a long way towards calming the passengers), a hijacker who succeeds in taking over a bullet proof cockpit (turning a security countermeasure into a vulnerability), or a hijacker that convinces everyone that she's a sky marshal". Although none of these scenarios seems to be particularly plausible, there is enough to them to suggest that the effectiveness of the security measures is likely to be over-estimated at 100%.

As discussed earlier, it could well be argued that the largest deterrent to an attempted hijacking is crew and passenger resistance. Experience shows that the actions of concerned citizens have foiled more attempted hijackings than hardened cockpit doors or air marshals. If this was the case, *R*(crew and passenger resistance) would be much greater than 16.7%.

While the above risk reductions are our best estimate, which in many cases are based on conservative assumptions, it is recognized that there is significant uncertainty in quantifying the effectiveness of security measures. Hence, results will be subject to sensitivity analyses that will also consider the minimum (lower bound) risk reduction needed for a security measure to be cost-effective.

Annual fatality rate due to aircraft hijacking in the absence of enhanced security measures

One possible estimate of fatalities due to 9/11-like aircraft hijackings in the absence of enhanced airline security might be zero, or, at any rate, near-zero. No one was killed by aircraft hijacking within the United States in the years before 2001 and therefore before the escalation of expenditures. That is to say, history strongly suggests one should not normally expect there to be very many deaths—or even any at all—from aircraft hijacking within the United States.

The 9/11 terrorist event was enormous both in direct financial costs and in the loss of life when it took place, and that continues to be true today: there has never been a terrorist attack of remotely that magnitude. As Sandler and Enders (2005) note, "the casualties on 9/11 represent a clear outlier with deaths on this single day approximately equal to all transnational terrorist-related deaths recorded during the entire 1988–2000 period". With this in mind, one could potentially remove that outlier from consideration on the grounds that it may well remain a (horrific) aberration with little relevance to the future since "9/11 could join the Trojan Horse and Pearl Harbor among stratagems so uniquely surprising that their very success precludes their repetition," and, accordingly "al-Qaeda's best shot may have been exactly that" (Seitz 2004; Mueller 2002).

However, while it may be reasonable to leave 9/11 out of the statistics, it is not conservative, and, since hardened cockpit doors and air marshals are principally designed to prevent a replication of 9/11, this event needs to be included in the analysis. Among terrorist groups, al-Qaeda is the only one that actually advocates attacking the United States itself (Gerges 2005). As the threat to the U.S. homeland is from Al-Qaeda, it would be reasonable to consider the period of a heightened threat from Al-Qaeda to be a suitable time period for the estimation of fatality rate—this is a 10-year period 1992–2001. Accordingly, we will assume that, in the absence of enhanced security measures, there would be a 9/11 replication every 10 years in the United States. That is, the annual fatality rate before enhanced security measures is 300 per year.

Results and discussion

Risk reduction

Hardening cockpit doors has the highest risk reduction (16.67%) at lowest additional cost of $40 million. On the other hand, the Federal Air Marshal Service costs $900 million pa but reduces risk by only 1.67%. The Federal Air Marshal Service may be more cost-effective if it is able to show extra benefit over the cheaper measure of hardening cockpit doors. However, the Federal Air Marshal Service seems to have significantly less benefit which means that hardening cockpit doors is the more cost-effective measure.

Cost-benefit analysis

Hardened cockpit doors

If there is no Federal Air Marshal Service, hardening cockpit doors reduces risk by *R* (hardened cockpit doors)=16.67% at an additional cost of $40 million; hence:

- C_R=$40 million per year
- *R*=*R*(hardened cockpit door)=16.67%
- Annual fatality rate before enhanced security measures=300 fatalities per year

It follows from Eq. (2) that the annual cost per life saved (C_{LS}) is $800,000.

An annual cost per life saved of $800,000 is less than the regulatory goal of $1–$10 million per life saved. If the effectiveness of pre-boarding security is increased from 50% to 80%, then Eq. (3) shows that the effectiveness of hardened cockpit doors is reduced to *R*=6.67%, and the annual cost per life saved is increased to $2 million. If (1) effectiveness of hardened cockpit doors is double that of crew and passenger resistance or air marshals or (2) crew and passengers do not resist a hijacking—*R*(crew and passenger resistance)=0%, then in both scenarios *R*=25% and the annual cost per life saved is reduced to $533,000. If it is assumed that the increased expenditure on pre-boarding security has only been "minimally effective" (Schneier 2006), *R*(pre-boarding)=0% and in that case R doubles to 33.34% and the annual cost per life saved is reduced to only $400,000. In all these cases the annual cost per life saved is less than $10 million.

Figure 2 shows annual cost per life saved as a function of *R*(hardened cockpit door). The annual cost per life saved is greater than $10 million only when *R* is less than 1.33%. Hence, the lower bound of risk reduction for hardened cockpit doors to be viewed as cost-effective is only 1.33%. Since security experts believe that strengthening cockpit doors is one of the few security measures post 9/11 to be effective (Schneier 2006; Maley 2008) then it is highly likely that the risk reduction achieved by the hardening of cockpit doors is well in excess of 1.33%. So under this analysis, hardening cockpit doors is a cost-effective security measure, a finding that

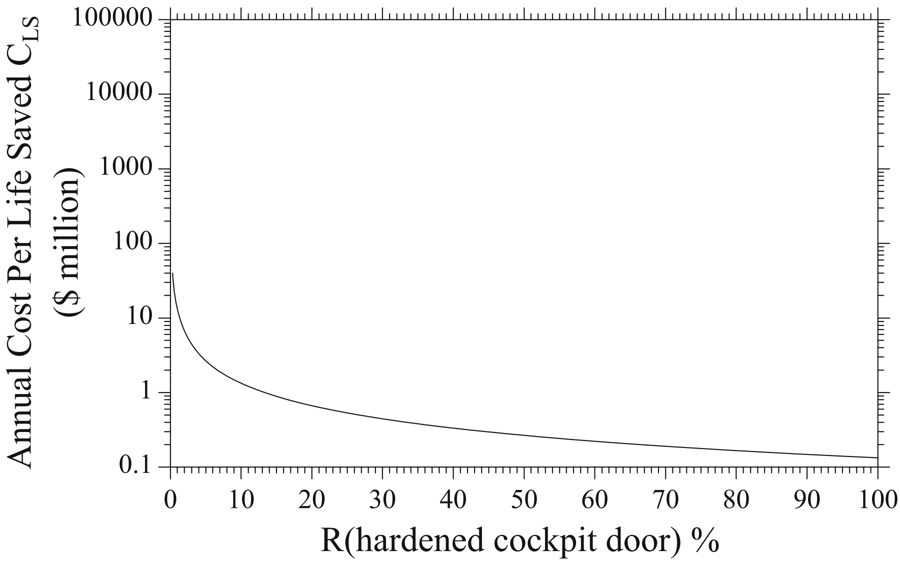

Figure 2 Annual cost per life saved for risk reduction caused by hardening cockpit doors

is not overly sensitive to the relative weightings of risk reduction between security measures.

Federal Air Marshal Service

The Federal Air Marshal Service reduces risk by 1.67% at an additional cost of $900 million, hence:

- C_R=$900 million per year
- R=R (Federal Air Marshal Service)=1.67%
- Annual fatality rate before enhance security measures=300 fatalities per year

It follows from Eq. (2) that the annual cost per life saved is $180 million.

An annual cost per life saved of $180 million is greatly in excess of the regulatory goal of $1–$10 million per life saved. If the effectiveness of pre-boarding security is increased from 50% to 80% (R=0.67%), the annual cost per life saved increases to $450 million. If (1) effectiveness of air marshals is double that of crew and passenger resistance or hardened cockpit doors or (2) crew and passengers do not resist a hijacking—R(crew and passenger resistance)=0%, then in both scenarios R= 2.5% and the annual cost per life saved becomes $120 million. If it is assumed that increased expenditures on pre-boarding security are ineffective (R(pre-boarding)= 0%), then R(Federal Air Marshal Service) doubles to 3.34% and the annual cost per life saved becomes $90 million. In all these cases the annual cost per life saved is well in excess of $10 million.

Figure 3 shows annual cost per life saved as a function of R(air marshals) and Pr (air marshals on plane). At the extreme, it could be assumed that air marshals are the only effective security measure: R(air marshals)=100% and therefore $R(\text{Federal Air Marshal Service}) = 100\% \times \Pr(\text{air marshals on plane}) = 0.1$. Even with this best

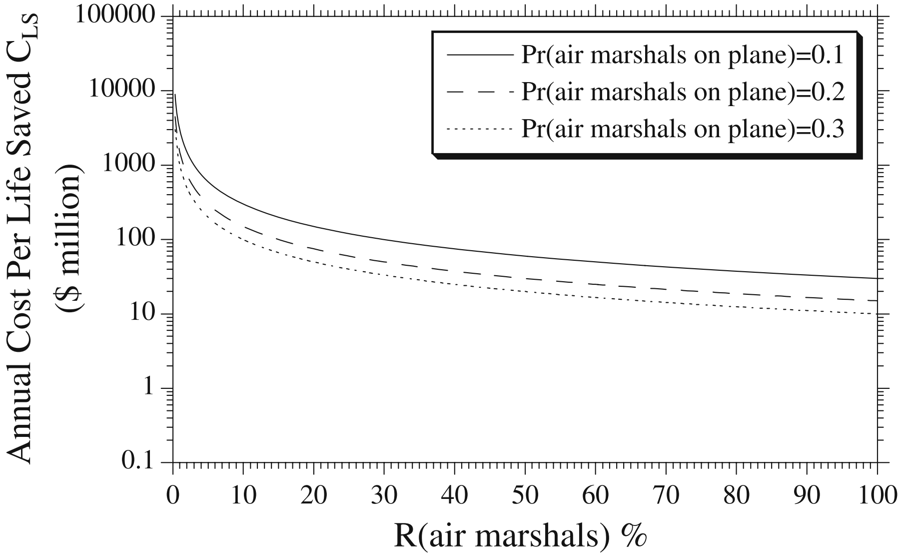

Figure 3 Annual cost per life saved for risk reduction caused by federal air marshal service. Note: R (Federal Air Marshal Service)=R(air marshals) x Pr(air marshals on plane)

case, the annual cost per life saved remains high at $30 million. If Pr (air marshals on plane) is doubled to 0.2, annual costs per life saved are half of those calculated above, which would still be in excess of the regulatory goal of $1–$10 million per life saved. The lower bound of risk reduction caused by the Federal Air Marshal Service to be viewed as cost-effective is thus *R*(Federal Air Marshal Service)=30%. So the Federal Air Marshal Service would only be cost-effective if we assume: (1) that without airline safety measures 300 people would die each year from replications of 9/11, (2) the only effective security measure is the Federal Air Marshal Service, and (3) air marshals ride on more than 30% of all passenger airplanes. This is not likely to be the case, particularly since there is no evidence to date of air marshals foiling a terrorist event. It would also have to be proven that the Federal Air Marshal Service has a significant deterrent effect (i.e. deter terrorists from hijacking an aircraft) for it to be cost-effective, but this would be ameliorated by the low percentage of flights that they can cover. Therefore, all reasonable combinations of security measure effectiveness suggest that the Federal Air Marshal Service fails a cost-benefit analysis.

Discussion

As discussed previously, the effectiveness of security measures is likely to be over-estimated because we assume that loss of life due to aircraft hijacking is completely eliminated (*R*=100%) and because we ignore the possibility of scenarios in which hijackers can still succeed despite the presence of new security measures on aircraft. There may also be other aviation security measures, such as a double cockpit door, that could further enhance security. If the loss of life due to aircraft hijacking is not completely eliminated or if other security measures are implemented, the percentage risk reductions for hardened cockpit doors and the Federal Air Marshal Service will be lowered, leading to higher annual costs per life saved. Accordingly, the Federal Air Marshal Service would be deemed even less cost-effective. However, even an order of magnitude reduction in the effectiveness of hardened cockpit doors (resulting in cost per life saved of $8 million) would not change the conclusion that hardened cockpit doors appears to be a cost-effective aviation security measure.

Whereas hardening cockpit doors could be a cost-effective security measure, the Federal Air Marshal Service fails a cost-benefit analysis. To be sure, the cost-benefit analysis is preliminary and the annual cost per life saved inferred herein are estimates (albeit conservative) only, but the magnitude of the costs are large and even if some best estimates are in error by 1,000% or more, this will not change the cost-benefit conclusions.

Note that the costs per life saved and findings described herein are very similar also for Australian aviation security measures (Stewart and Mueller 2008b). The report by Stewart and Mueller (2008b) assessing the risks, costs and benefits of Australian aviation security measures showed that strengthening cockpit doors is cost-effective whereas the Australian Air Security Officer program (air marshals) is not.

In addition to life-safety considerations, economic criteria such as reduced property damage and reduced GDP are other benefits of security measures. It has been estimated in a RAND report by Zycher (2003) that these types of economic benefits are approximately equal to the value of lives saved. Zycher also recommends that the total economic cost of security measures is at least twice the direct public expenditure due to the fact that "government must obtain such resources, whether now or in the future, through the tax system (or through such explicit taxation as inflation), which imposes indirect costs upon the economy in the form of resource misallocation" (Zycher 2003). Hence, in this case the effect of marginal cost of government spending and the doubling of benefits due to inclusion of economic criteria tend to cancel each other out, resulting in little change in annual costs per life saved calculated in the present analysis. Hence, it is expected that more comprehensive cost-benefit analyses that consider economic and financial matters will not change the conclusions of this paper.

Risk reduction measures that cost tens or hundreds of millions of dollars per life saved cannot be justified on rational life-safety grounds—or, essentially, on moral ones. If some of the additional federal government and private sector spending on aviation security were invested in other hazard or risk reduction programs, many more lives would have been saved. For example, Ahrens (2007) estimates that 890 lives could be saved annually if all homes had a working smoke alarm and Tengs and Graham (1996) estimate that an investment of $200,000 per year in smoke alarms will save one life. From this it can be inferred that an expenditure of only $5 million per year will save approximately 25–30 lives per year. Similar examples can be found for other risk reduction measures or regulations. While these numbers are approximate, they do illustrate the significant opportunity costs of the Federal Air Marshal Service. If risks from security threats other than 9/11 type attacks are considered significant enough, then this large expenditure may be used more efficiently for other security and counter-terrorism programs. Moreover, in a multi-hazard environment, such expenditure could instead be invested in a wide range of more cost-effective risk reduction programs such as flood protection; vaccination, screening and other health programs; vehicle and road safety; occupational health and safety.

Finally, this paper provides a starting point for further discussion. The assumptions and quantifications made here can be queried, and alternate hypotheses can be tested in a manner which over time will minimize subjectivity and parameter uncertainty inherent in an analysis for which there are little accurate data. This should lead to more widespread understanding and agreement about the relative cost-effectiveness of aviation and other counter terrorism security measures.

Conclusions

Schneier (2006) concludes that the only two effective antiterrorism countermeasures implemented after 9/11 were strengthening cockpit doors and passengers learning they need to fight back. Athol Yates, Executive Director of the Australian Homeland Security Research Centre says that air marshals are of 'questionable' security value, and that "hardening the cockpit doors and changing the protocols for hijacking has made it harder for terrorists to get weapons on board an aircraft and take control of it" (Maley 2008). The assessment in this paper supports these conclusions. Even assuming that enhanced airline security measures prevent one 9/11 replication each decade, the $900 million expenditure per year for the Federal Air Marshal Service fails a cost-benefit analysis. On the other hand, spending $40 million per year to harden cockpit doors under that assumption appears to be a cost-effective security measure. While defense-in-depth and layered approaches to security have merit, in this instance the Federal Air Marshal Service carries with it a great opportunity cost and may be one layer too many.

Acknowledgements Part of this work was undertaken while the first author was a visiting scholar at the Mershon Center for International Security Studies at Ohio State University. He greatly appreciates the assistance and financial support of the Mershon Center. The first author also appreciates the financial support of the Australian Research Council.

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