Aviation Security, Risk Assessment, and Risk Aversion for Public Decisionmaking

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Abstract

This paper estimates risk reductions for each layer of security designed to prevent commercial passenger airliners from being commandeered by terrorists, kept under control for some time, and then crashed into specific targets. Probabilistic methods are used to characterize the uncertainty of rates of deterrence, detection, and disruption, as well as losses. Since homeland security decisionmakers tend to be risk-averse because of the catastrophic or dire nature of the hazard or event, utility theory and Monte Carlo simulation methods are used to propagate uncertainties in calculations of net present value, expected utility, and probabilities of net benefit. We employ a "break-even" cost-benefit analysis to determine the minimum probability of an otherwise successful attack that is required for the benefit of security measures to equal their cost. In this context, we examine specific policy options: including Improvised Physical Secondary Barriers (IPSBs) in the array of aircraft security measures, including the Federal Air Marshal Service (FAMS), and including them both. Attack probabilities need to exceed 260 percent or 2.6 attacks per year to be 90 percent sure that FAMS is cost-effective, whereas IPSBs have more than 90 percent chance of being cost-effective even if attack probabilities are as low as 6 percent per year. A risk-neutral analysis finds a policy option of adding IPSBs but not FAMS to the other measures to be preferred for all attack probabilities. However, a very risk-averse decisionmaker is 48 percent likely to prefer to retain FAMS even if the attack probability is as low as 1 percent per year—a level of risk aversion exhibited by few, if any, government agencies. Overall, it seems that, even in an analysis that biases the consideration toward the opposite conclusion, far too much may currently be spent on security measures to address the problem of airline hijacking, and many spending reductions could likely be made with little or no consequent reduction of security. © 2013 by the Association for Public Policy Analysis and Management.

INTRODUCTION

This paper evaluates security measures designed to prevent commercial passenger airliners from being commandeered by small bands of terrorists, kept under control for some time, and then crashed into specific targets. Concern about this possibility has been sufficient to warrant the deployment of antiaircraft missile batteries at the Beijing and London Olympics. We estimated the risk reduction from existing measures using systems reliability techniques that specifically consider rates of

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deterrence, detection, and disruption for each layer of security. This requires the quantification of threat probability, risk reduction, losses, and security costs. We employed a "break-even" cost-benefit analysis that determined the minimum probability of an otherwise successful attack that would be required for the benefit of security measures to equal their cost.[1]

Terrorism is a threat with characteristics that frighten people and make them risk-averse. Among these characteristics are dread (or fear), the involuntary and seemingly random nature and catastrophic potential of the hazard, the sense that there is little preventive control, the seeming certainty that there will be fatalities, and the large number of people exposed (Wilson & Crouch, 1987).

Governments should be risk-neutral because they have a high degree of cost and benefit diversification not available to individuals (Ellingwood, 2006; Sunstein, 2002). Hardaker, Fleming, and Lien (2009, p. 256) have acknowledged that "policy-making is a risky business," but observed that "regardless of the varied desires and political pressures, we believe that it is the responsibility of analysts forcefully to advocate rational decision methods in public policy-making, especially for those with high risk." If rational approaches to public policymaking are not applied, politically driven processes "may lead to raising unnecessary fears, wasting scarce resources, or ignoring important problems" (Paté-Cornell, 2002, p. 644). Indeed, the U.S. Office of Management and Budget specifically states that the use of expected values (an unbiased estimate) is appropriate for government cost-benefit calculations (Office of Management and Budget [OMB], 1992). This entails using mean or average estimates for risk and cost-benefit calculations, and not worst-case or pessimistic ones.[2]

Nonetheless, public policy decisionmaking for low probability–high consequence events is often characterized by risk aversion (Cha & Ellingwood, 2012), as many homeland security measures fail a cost-benefit analysis using standard expected value methods of analysis (Stewart & Mueller, 2008, 2011, 2013). This suggests that the relevant policymakers must be considerably risk-averse when they approve such measures (Stewart, Ellingwood, & Mueller, 2011).

Utility theory can be used to factor risk aversion into the decision process, and this paper will infer utility functions that represent the level of risk averseness of the U.S. Department of Homeland Security (DHS) when justifying existing and proposed aviation security policies. Stewart and Mueller (2013) developed a simple systems reliability model for aviation security using single-point estimates of risk reduction and losses, and a risk-neutral decision analysis. This paper extends this work considerably by (1) including the effect of deterrence in estimating risk reduction, (2) developing conditional probabilities for detection rates since security measures are not perfectly substitutional, (3) characterizing detection rates, risk reduction, and losses as probabilistic variables allowing confidence intervals of policy preferences to be calculated, and (4) using utility theory to quantify levels of risk aversion. The key issues are how high do attack probabilities need to be for aviation security measures to be cost-effective? And if attack probabilities are low, what is the degree of risk averseness necessary for a decisionmaker to accept that spending up to $4 billion per year to prevent a 9/11 type attack is justified?

[1] For a literature review of probabilistic terrorism risk assessment, see Stewart and Mueller (2013).

[2] Paté-Cornell (2002, p. 634) elaborates on this point: "If risk ranking is recognized as a practical necessity and if resource limitations are acknowledged, the maximum overall safety is obtained by ranking the risks using the means of the risk results (i.e., expected value of losses)."

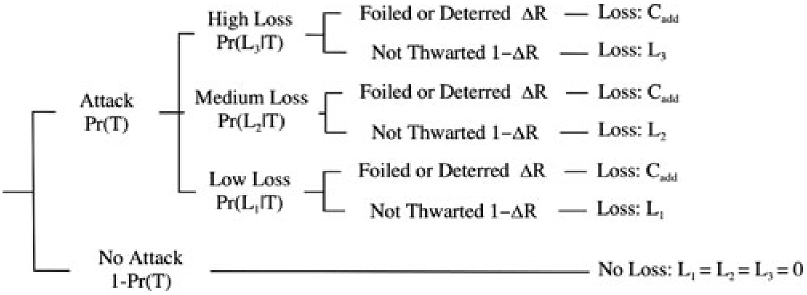

High Loss
Pr(L3|T)
Foiled or Deterred ΔR — Loss: C_add
Not Thwarted 1−ΔR — Loss: L3
Attack
Pr(T)
Medium Loss
Pr(L2|T)
Foiled or Deterred ΔR — Loss: C_add
Not Thwarted 1−ΔR — Loss: L2
Low Loss
Pr(L1|T)
Foiled or Deterred ΔR — Loss: C_add
Not Thwarted 1−ΔR — Loss: L1
No Attack
1-Pr(T)
No Loss: L1 = L2 = L3 = 0

Figure 1. Event Tree of Losses.

RISK-BASED DECISION SUPPORT FRAMEWORK

A standard definition of risk is:

$$\text{Risk} = \text{Threat} \times \text{Vulnerability} \times \text{Consequences}. \tag{1}$$

This is consistent with the conceptual framework adopted by the DHS (National Research Council [NRC], 2010) and with risk analyses for many applications (Kaplan & Garrick, 1981; Stewart & Melchers, 1997).

An aversion to risk arises mostly from the magnitude of the consequences or large losses from a terrorist event. Utility theory provides a means of evaluating the risk preferences of the interested parties under choice uncertainty. The attribute (x) under consideration is monetized costs of security measures and losses sustained from a terrorist attack. For illustrative purposes, three loss attributes are considered, $i = 1$, 2, and 3 to represent low, medium, and high consequences, respectively. Airlines or governments may impose stricter security requirements in an attempt to placate a frightened public in the event of a foiled attack. These additional costs will depend on at what stage the plot was foiled. We assume four stages: $j = 1$: deterred, $j = 2$: detected prior to boarding, $j = 3$: foiled in flight, and $j = 4$: aircraft downed by antiaircraft measures. The event tree of events that lead to losses L_i is given in Figure 1. The expected utility $E[u]$ from this event tree is

$$E[u] = \underbrace{\Pr(T)}_{\text{Threat}} \sum_{i=1}^{3} \underbrace{\Pr(L_i\,|T)}_{\text{Vulnerability}} \underbrace{\left[\begin{array}{l} \sum_{j=1}^{4} \Delta R_{\text{j}} u\left(C_{\text{security}} + C_{add,j}\right) + \\ + \left(1 - \sum_{j=1}^{4} \Delta R_{\text{j}}\right) u\left(C_{\text{security}} + L_i\right) \end{array}\right]}_{\text{Consequences}}$$

$$+ \underbrace{(1 - \Pr(T))\, u\left(C_{\text{security}}\right)}_{\text{no attack}} \quad 0 \le \Pr(T) \le 1 \tag{2}$$

where $u(x)$ is the utility for cost x expressed as a utility function for cost consequences; the probability of attack Pr(T) is the likelihood that a successful terrorist attack will take place where the security measures are not in place (i.e., the attack will down the airliner given no security measures are in place); Pr($L \mid T$) is the conditional probability of a loss given occurrence of the threat (vulnerability); the reduction in risk (ΔR_j) is the degree to which security measures reduce the likelihood of a successful terrorist attack or the losses sustained in such an attack;

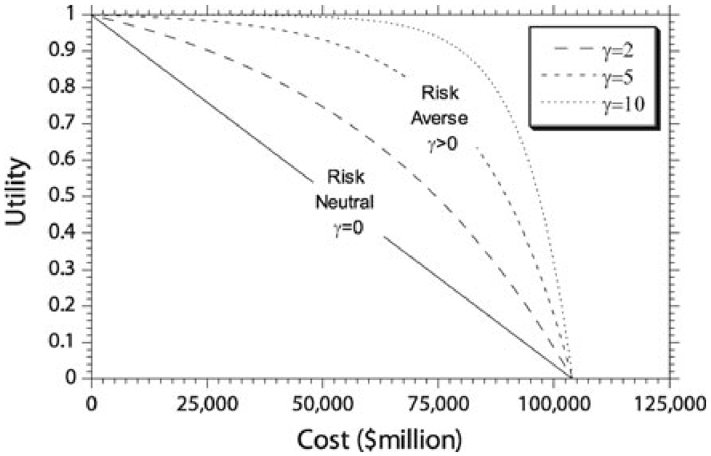


Figure 2. Risk-Neutral and Risk-Averse Utility Functions.

C_{security} is the cost associated with security measures that lead to risk reduction; and $C_{\text{add},j}$ is the additional cost caused by a foiled plot resulting in increased security requirements, and a more risk-averse traveling public and regulators.

The objective of the decisionmaking process is to maximize the expected utility, and so an option is preferable if it has a higher utility. Utility is highest ($u = 1.0$) when costs and losses are zero, and lowest ($u = 0$) when costs are a maximum. A risk-neutral linear utility function is appropriate for decisionmakers in governments or large companies that can afford to sustain a loss on a 50/50 chance ($P = 0.5$) of making an equally substantial profit. However, this would not be true among individuals or corporations making decisions involving monetary values that are large in relation to their working capital (Bickel, 2006). These decisionmakers would only take a gamble if the risk of large loss is small. Such decisionmakers are risk-averse, and their preferences are manifested in a concave utility function. In other words, they are prepared to settle for a guaranteed expected loss (avoid the gamble) rather than accept a risk of an even larger loss. That is, the higher the level of risk averseness, the higher the willingness to pay. Figure 2 shows risk-neutral and risk-averse utility functions. The utility function is

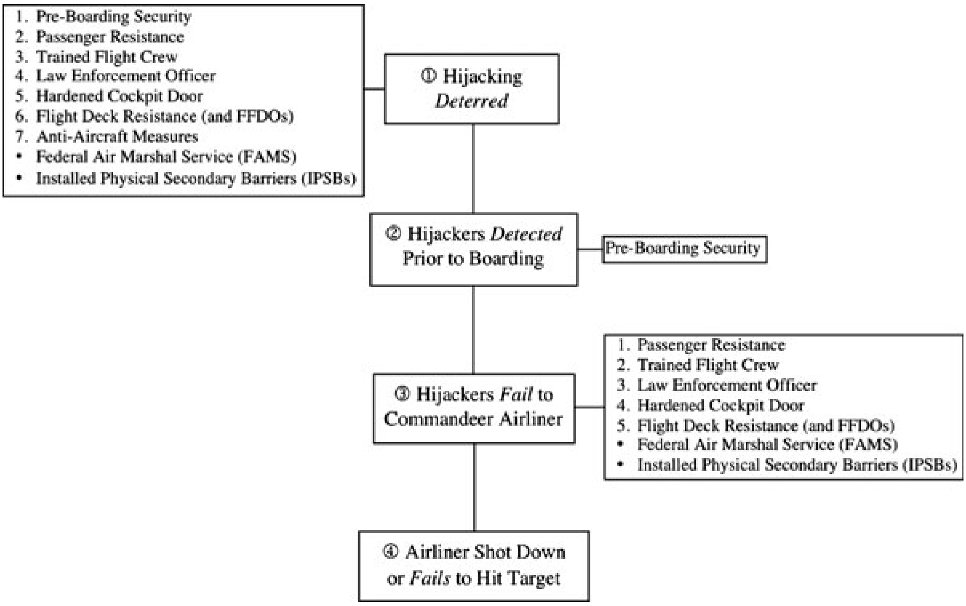
$$u(x) = \frac{1}{1 - e^{-\gamma}} \left(1 - e^{-\gamma\left(\frac{x_{\max} - x}{x_{\max}}\right)}\right) \quad \gamma \geq 0 \tag{3}$$

where γ is the risk-averse shape factor. As γ increases, the utility function becomes more concave, and so the level of risk averseness increases.

Layers of Aviation Security

We separated the layers of aviation security into four stages (see Figure 3).[3] However, although we have a full model of the process, we did not include one impediment to a successful attack: the general incompetence and poor tradecraft of terrorists, particularly in complicated plots (Aaronson, 2013; Kenney, 2010; Mueller, 2013; Mueller & Stewart, 2012).

[3] For more details of costs and characteristics of security measures, see Stewart and Mueller (2013).


1. Pre-Boarding Security
2. Passenger Resistance
3. Trained Flight Crew
4. Law Enforcement Officer
5. Hardened Cockpit Door
6. Flight Deck Resistance (and FFDOs)
7. Anti-Aircraft Measures
• Federal Air Marshal Service (FAMS)
• Installed Physical Secondary Barriers (IPSBs)
① Hijacking Deterred
② Hijackers Detected Prior to Boarding
Pre-Boarding Security
③ Hijackers Fail to Commandeer Airliner
1. Passenger Resistance
2. Trained Flight Crew
3. Law Enforcement Officer
4. Hardened Cockpit Door
5. Flight Deck Resistance (and FFDOs)
• Federal Air Marshal Service (FAMS)
• Installed Physical Secondary Barriers (IPSBs)
④ Airliner Shot Down or Fails to Hit Target

Source: Air Line Pilots Association International, 2007.

Figure 3. Reliability Block Diagram for Aviation Security Measures.

Stage 1. Terrorists Are Deterred from Attempting an Airliner Hijacking

If security measures deter an attack in the first place, there are unlikely to be any secondary costs, because a deterred attack will not inspire demands for additional security spending. Many reasons might deter a terrorist contemplating a hijacking. In addition to concerns about security measures, a terrorist might be deterred, for example, by the belief that the hijacking will be counterproductive to the cause or by an unwillingness to commit suicide.

Stage 2. Terrorists Attempt a Hijacking, Are Prevented from Boarding

A considerable array of security measures is specifically designed to prevent a terrorist from boarding. These include *intelligence*, *international partnerships*, *customs and border protection*, *joint terrorism task forces*, *the no-fly list*, *passenger prescreening*, *behavioral detection officers*, *travel document checkers*, *checkpoint/transportation security officers*, *transportation security inspectors*, *crew vetting*, and *random employee screening*. Any public demand for enhanced security expenditures in response to an attack prevented at this level is likely to be modest.

Stage 3. Terrorists Succeed in Boarding, Are Foiled in the Attempt to Commandeer the Flight Deck

One reason for the extent of the losses in 2001 was the lack of *crew and passenger resistance* to the hijackings. The 9/11 attacks radically changed this situation. As demonstrated on the fourth plane on 9/11, passengers and crew will now fight back, particularly if there is any indication that the terrorists' intent is to enter the cockpit. Passenger and crew reactions were also effective in subduing the shoe bomber Richard Reid in his attempt to blow up an airliner over the Atlantic less than four months after 9/11, and in the 2009 Christmas Day plot in which a terrorist hid plastic explosives in his underwear on a Northwest Airlines flight on its way to Detroit from Europe.

Law enforcement officers (LEOs) are on some flights for reasons other than countering terrorism, such as escorting prisoners or protecting VIPs. However, their numbers are small and their impact on security is likely to be low.

Since 2003, the Federal Aviation Administration (FAA) has required airlines to install *hardened cockpit doors* to protect cockpits from intrusion and small-arms fire or fragmentation devices. The FAA also requires that cockpit doors remain locked and cockpit access controlled. There is little doubt that hardened cockpit doors will deter and delay a hijacker's attempt to enter the cockpit. However, if attackers are somehow able to get into the flight deck, the doors become a security device that could protect them.

Another layer of security is *flight deck resistance*. With the horrific experience of 9/11 behind them, pilots are very likely to put up a fight against any cockpit penetration, whatever their training or armaments. The Federal Flight Deck Officer (FFDO) program enhances their ability to do so by allowing pilots and crew members to transport and carry firearms to defend the flight deck. It is estimated that 16 to 20 percent of pilots will be FFDOs by 2012 (Elias, 2009), and the program costs only $22 million annually. For its modest cost, and higher coverage than air marshals (discussed below), the Airline Pilots Association International considers the FFDO program to be "an extremely successful and cost-effective layer of aviation security" (Moak, 2011). The Coalition of Airline Pilots Associations recommends doubling the FFDO budget over five years, and Seidenstat (2009) argues that "arming pilots and training crew members to deal with hijackers appear to serve as substitutes for placing marshals on flights and seem to be effective and far less costly" (p. 158).

There are now some 2,500 to 4,000 *air marshals*, up from 33 before 9/11 (Elias, 2009), and by FY2012 the budget for the Federal Air Marshal Service (FAMS) had reached $990 million (Department of Homeland Security [DHS], 2012). In addition, airlines are expected to provide free seats for air marshals. It has been estimated that air marshals ride on less than 5 percent of flights in the United States (Elias, 2009). These are deemed to be high-risk flights, based on intelligence reports. Exactly how that risk has been determined is unclear, however, particularly since air marshals have made no arrests related to terrorism. The presence of air marshals is likely to have a deterrent effect, but this is offset by the low percentage of flights they can cover. In addition, some crew and passengers may be reluctant to be the first to confront a hijacker if they believe an air marshal is on board.[4]

When the cockpit door is opened for rest periods, toilet breaks, and meals, the protective benefits of a hardened cockpit door is reduced. A 2011 Radio Technical Commission for Aeronautics (RTCA) report examines a hijacking scenario involving "a team of highly trained, armed, athletic individuals" (p. 4) who might be able to take over the flight deck during a door transition in a matter of seconds. Under those circumstances, passengers and crew would scarcely have time to assess the situation, realize the dire threat, communicate with other passengers, and process other information needed for them to summon the courage to fight back. The RTCA report concludes that, under that scenario, "passengers are not considered a predictably reliable option for preventing an attempted violent or sudden breach of the flight deck," and it completely excludes "the possibility of passenger intervention

[4] Air marshals might be helpful in other terrorist situations—for example, if a passenger tried to blow up the airliner. However, their added value over crew and passenger resistance is likely to be rather small because they are present on only a rather small percentage of flights and because they are likely to be seated far from any potential bomber. However, FAMS may provide some flexibility as air marshals can be deployed at short notice for emerging threats.

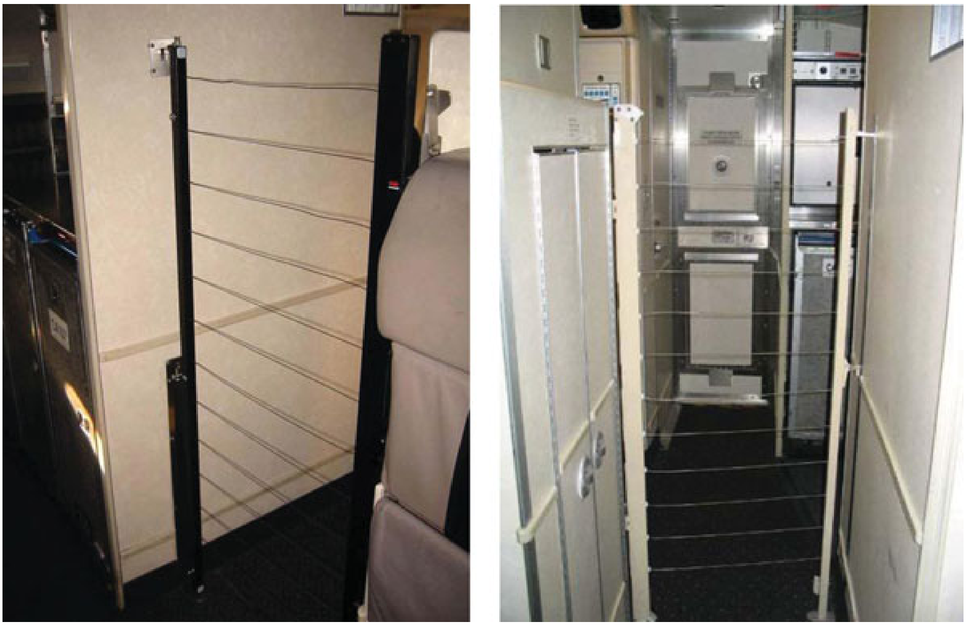


Figure 4. Fully Deployed Installed Physical Secondary Barrier.

as a mitigating measure" from its consideration (RTCA, 2011, p. 29). To a perhaps somewhat lesser degree, the same may hold for air marshals.[5]

To deal with this contingency, the Air Line Pilots Association International has concluded that "the reinforced flight deck door does not provide a complete solution for securing the flight deck" (Air Line Pilots Association International [ALPA], 2007, p. 2), and in 2004 United Airlines installed *Improvised Physical Secondary Barriers (IPSBs)* on its entire fleet of passenger aircraft. This is "a lightweight device that is easy to deploy and stow, installed between the passenger cabin and the cockpit door, that blocks access to the flight deck whenever the reinforced door is opened in flight" (ALPA, 2007, p. 3; see Figure 4). The fact that a cabin crew member must be on the scene to deploy the secondary barrier adds another complication for would-be hijackers. The cost of an IPSB for a single aircraft is approximately $30,000 in 2011 dollars. Since there are approximately 6,000 commercial aircraft in the United States, this equates to approximately $200 million, and this cost is annualized over the 20-year design life of an aircraft with a 3 percent discount rate. This equates to a present value cost of $13.5 million per year, or $18.9 million per year for a 7 percent discount rate. We will round this to $20 million per year to be conservative.

Public demands for enhanced security expenditures in response to an attack foiled at this level are likely to be very substantial. There is also likely to be a reduction in the demand for air travel.

Stage 4. Terrorists Succeed in Commandeering the Airliner, Are Kept from Flying It into Their Target

[5] Although flight attendants receive little or no training in the use of force, many airlines have instituted procedures during door transition such as galley trolleys to block access to the flight deck. The report concludes, however, that this did "not produce satisfactory results" (RTCA, 2011, p. 27).

The final layer of security concerns *antiaircraft defensive measures* put into place after 9/11 (Elias, 2009). If a pilot were able to transmit to air controllers that the plane was undergoing a violent hijacking attempt (or if passengers or cabin crew members were able to use their phones to warn authorities), antiaircraft measures might immediately be scrambled to shoot down or ground the captured airliner before it could reach an intended target. Public demands for enhanced security expenditures in response to an attack foiled at this level are likely to be huge. There is also likely to be a very substantial reduction in the demand for air travel.

EVALUATING THE REDUCTIONS IN RISK

For any security measure, the risk reduction can vary from 0 to 100 percent. Fault trees and logic diagrams, together with systems engineering and reliability approaches, will aid in assessing complex interactions involving threats, vulnerabilities, and consequences (Stewart & Melchers, 1997). Applying this approach, Figure 3 shows a reliability block diagram used to represent the system of deterring or foiling a terrorist hijacking on a commercial airplane as discussed above. Existing measures (or "business as usual") include all layers of security described above, including FAMS but not IPSBs. While many policy options and strategies are available, we will examine three that deal with FAMS (an expensive measure) and IPSBs (an inexpensive one):

1. Include both IPSBs and FAMS in the array of security measures.
2. Include IPSBs but not FAMS in the array of security measures.
3. Exclude both FAMS and IPSBs from the array of security measures.

We recognize that security measures may not be perfectly substitutional (i.e., independent of each other). For example, removing one layer of security may alter the systems model and/or detection rates of other layers of security. Therefore, we assumed a series system where many event probabilities for all layers of security are treated as conditional probabilities. Hence, Pr(foiled by door | no IPSB) denotes that the effectiveness of the hardened cockpit door will be influenced by whether an IPSB is present, since the absence of an IPSB may mean that flight crew are more careful during door transitions. The probability that an attempt to hijack an aircraft is deterred or fails to be successful is a measure of total risk reduction equal to

$$R = 1 - \left\{ \begin{array}{l} [1 - \Pr(\text{deterred})] \\ \times [1 - \Pr(\text{detected preboarding})] \\ \times [1 - \Pr(\text{failed to commandeer aircraft})] \\ \times [1 - \Pr(\text{antiaircraft measures})] \end{array} \right\}. \tag{4}$$

The two security measures under examination (FAMS and IPSBs) affect the stage 1 probability of deterrence Pr(deterred), and the stage 3 probability Pr(fail to commandeer aircraft). The latter probability is affected by interactions between the hardened cockpit door, flight deck resistance, and the three policy scenarios for FAMS and IPSBs set out above. The derivations of these probabilities are described in the Appendix.[6] Equation (4) shows the benefits of multiple layers of security. For example, if each of the four probabilities in equation (4) is 50 percent, the overall

[6] All appendices are available at the end of this article as it appears in JPAM online. Go to the publisher's Web site and use the search engine to locate the article at http://www3.interscience.wiley.com/cgi-bin/jhome/34787.

Table 1. Words of estimative probability and triangular distribution.

Certain	100%
Almost certain	93%
Highly probable	85%
Probable	75%
Chances about even	50%
Probably not	30%
Almost certainly not	7%
Impossible	0%

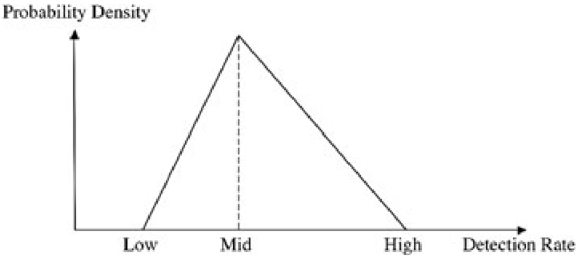


Table 2. Deterrent rates for aviation security measures in stage 1.

	Low (%)	Mid (%)	High (%)	Notes
Preboarding	7	30	50	Probably not. Screening technologies are imperfect.
Passengers/crew	7	30	50	Probably not. May not be able to react in time.
LEO	0	0	7	Very low probability of being on a flight.
Hardened cockpit door	7	30	50	Probably not. Flight deck still vulnerable during “door transitions” for a well-planned and coordinated attack.
Flight deck resistance	7	30	50	Probably not. Probability of FFDOs being on a plane is 15–20%.
Antiaircraft measures	7	30	50	Probably not, particularly when flight crew ability to contact the outside is considered.
IPSBs	7	50	75	Chances about even. Ameliorates vulnerability during “door transitions” and are on every aircraft.
FAMS	0	7	30	Almost certainly not. FAMS is on a very small proportion of flights. May not react in time.

risk reduction is high, $R = 93.75$ percent. Additional layers of security will increase this risk reduction, but the additional risk reduction of each layer (ΔR) will become progressively smaller.

Note that equation (4) is based on a single threat scenario, whereas security measures are often designed to deal with a range of threats. A more detailed and comprehensive study is required to properly model the complex interactions and interdependencies in aviation security. Nonetheless, equation (4) provides a basis to assess the influence and sensitivity of policy options on risk reduction.

Words of estimative probability are shown in Table 1 (adapted from Fletcher, 2011), and they are then applied to deterrence and security measures in Tables 2–4. Low, mid (best estimate), and high rates help represent uncertainty in parameter estimation and allow lower and upper bounds of risk reductions to be inferred. A triangular probability distribution is used to represent uncertainty of the rates; see Table 1. Martonosi and Barnett (2006) and Fletcher (2011), who was a Transportation Security Administration (TSA) employee, have provided some guidance on disruption rates for preboarding security stage 2 (Table 3). Since there is little (if any) quantitative data on these rates, it is more tractable to assign words such as

Table 3. Disruption rates for aviation security measures in stage 2.

	Low (%)	Mid (%)	High (%)	Notes
Preboarding	30	50	75	Chances about even. Metal detectors, X-ray machines, and full-body scanners will have high disruption rates. Martonosi and Barnett (2006) suggest that preboarding security screening has a detection rate of 50%, and Fletcher (2011) estimates 85% for detection prior to boarding. However, adaptive terrorists may develop a scheme that bypasses many layers of security.

probably not, *chances about even*, and so forth when assessing the effectiveness of security measures; Table 1 translates these words into probabilities.

We tended to err on the low side in estimating deterrence and disruption rates in Tables 2–4. This biases the analysis toward finding additional levels of security to be cost-effective. A sensitivity analysis conducted later assesses changes in risk reduction and cost-effectiveness if some of these rates are changed.

Monte Carlo simulation was used to calculate the mean and 10th and 90th percentiles that a hijacking would be unsuccessful (fail to strike its target) or total risk reduction (R); see Table 5. The likelihood of foiling a hijacking will be higher, and the potential for risk reduction for additional security measures will decrease, if the existing measures have higher deterrent or disruption rates or if additional factors not related to specific security measures are helping to deter a terrorist attempt. Table 5 shows that total risk reduction (R) was nearly 99 percent for the full array of existing measures excluding both IPSBs and FAMS. In the simulation where IPSBs were added, risk reduction increased to nearly 100 percent. The best estimate of additional risk reduction due to IPSBs was nearly 1 percent, and its upper bound was 2 percent, something that can be achieved with an expenditure of less than $20 million per year. Adding FAMS reduced risk by a negligible amount (less than 0.1 percent) while costing nearly $1 billion. This observation alone provides strong evidence that FAMS fails to be cost-effective.

A breakdown of risk reductions for each stage of aviation security (ΔR_j) showed that deterrence was responsible for 76 to 96 percent of risk reduction (see Table 6). Any opportunity for risk reduction by additional measures was rather low.

Direct Costs for Security Measures

The analysis will assess the security costs and risk averseness of the U.S. federal government. The FY2012 expenditure of the TSA on aviation security totals approximately $6.3 billion while employing over 55,000 personnel (DHS, 2012). This includes most of TSA's 21 layers of security, but it omits expenditures on one of them: FAMS. Because the cost of some layers of security in Figure 3, such as antiaircraft measures, will be borne by other agencies within the DHS or within the federal government, the $6.3 billion underestimates actual federal expenditures on aviation security. We rounded this to $7 to $8 billion per year. Much of the focus of aviation security is on (1) a 9/11-type attack where a commercial airliner is hijacked and crashed into a building or other target on the ground, and (2) a suicide bomber (including explosives in checked luggage) on commercial aircraft (Jackson et al., 2012). If we assume that preventing a 9/11-type attack accounts for half of the aviation

Table 4. Disruption rates for aviation security measures in stages 3 and 4.

	Low (%)	Mid (%)	High (%)	Notes
Passenger resistance	0	7	30	Almost certainly not.
Flight crew	0	7	30	Almost certainly not. The flight deck is vulnerable during door transition due to lack of training and due to the short reaction times needed to defeat an attacker.
LEO	0	0	7	Very low probability of being on a flight.
Existing Measures				
Foiled by door | no FAMS on board	30	75	93	Probable. If there is no IPSB, flight crew might be more careful about door transitions, leading to reduced vulnerability and higher disruption rate than Pr(foiled by door | IPSB fails | no FAMS on board).
Foiled by door | FAMS on board	50	85	93	Highly probable. FAMS will react quickly enough to detain hijacker, or slow hijacker allowing door to be closed. Since no IPSB, FAMS may be more alert and quicker to act in case of a threat to the cockpit door.
Foiled by door | FAMS	31	77	93	Equation (A.4)[a]
1. Add IPSBs				
Foiled by IPSB	50	75	93	Probable. Not 100% due to deployment malfunction or violation of procedures by crew during door transition.
Foiled by door | IPSB fails | no FAMS on board	30	50	75	Chances about even. Door is vulnerable during door transitions if IPSB fails and crew is unable to react in time.
Foiled by door | IPSB fails | FAMS on board	30	75	93	Probable. Requires FAMS to react quickly enough to detain hijacker, or slow hijacker allowing hardened cockpit door to be closed and locked.
FAMS on flight	5	20	40	FAMS are on no more than 5% of flights, but are placed on high-risk flights, so assume 20% coverage.
Foiled by door | IPSB fails | FAMS	30	55	82	Equation (A.7)
2. Add IPSBs, Remove FAMS				
Foiled by IPSB	50	75	93	See above.
Foiled by door | IPSB fails	30	50	75	See Pr(foiled by door | IPSB fails | no FAMS on board).
3. Remove FAMS and IPSBs				
Foiled by Door | No IPSB and no FAMS	30	75	85	Probable. Since there is no IPSB, flight crew might be more careful about door transitions, leading to reduced vulnerability and higher disruption rate than Pr(foiled by door | IPSB fails | FAMS on board).
Flight deck resistance in some cases enhanced by FFDO	7	15	30	If FFDOs are in every cockpit, they are 80–90% effective in foiling a hijacking. The probability of FFDOs being on a plane is 15–20%. Assumes only trained FFDOs will fight for their lives.

Table 4. Continued.

	Low (%)	Mid (%)	High (%)	Notes
Antiaircraft measures	7	30	50	Probably not. Authorities may not be able to deploy antiaircraft measures in time.

[a] All appendices are available at the end of this article as it appears in JPAM online. Go to the publisher's Web site and use the search engine to locate the article at http://www3.interscience.wiley.com/cgi-bin/jhome/34787.

Table 5. Risk reduction.

	Total risk reduction (R)			Increase in risk reduction		
	10th percentile (%)	Mean (%)	90th percentile (%)	10th percentile (%)	Mean (%)	90th percentile (%)
Existing measures	97.6	98.9	99.7	–	–	–
1. Include both IPSBs and FAMS	99.5	99.8	99.9	0.2	0.9	2.0
2. Include IPSBs, remove FAMS	99.4	99.7	99.9	0.2	0.8	1.9
3. Remove both FAMS and IPSBs	97.1	98.6	99.5	−0.1	−0.3	−0.6

Table 6. Tenth and 90th bounds of risk reductions for stages of deterrence or disruption.

Stage	Existing security measures ΔR_j (%)	1. Add IPSBs ΔR_j (%)	2. Add IPSBs, remove FAMS ΔR_j (%)	3. Remove FAMS and IPSBs ΔR_j (%)
$j = 1$ Deterred by security measures	76–90	85–96	83–95	73–89
$j = 2$ Detected preboarding	4–13	2–8	2–9	5–15
$j = 3$ Failed to commandeer aircraft	3–10	2–7	2–8	3–11
$j = 4$ Aircraft shot down	0.1–1	0–0.2	0–0.3	0.2–1.2
Total risk reduction (R)	97.6–99.7	99.5–99.9	99.4–99.9	97.1–99.5

security activities and expenditures, then this amounts to at least \$3 to \$4 billion per year, and adding in the cost of FAMS (\$990 million) gives a total of at least C_{security} = \$4 billion for existing measures including FAMS but not IPSBs. Adding IPSBs increases this by \$20 million. We assumed that the federal government would compensate airlines for IPSBs.

Security costs (C_{security}) for the policy scenarios are as follows:

1. Include both FAMS and IPSBs: \$4.02 billion.
2. Include IPSBs but not FAMS: \$3.02 billion (saving \$1 billion per year).
3. Include neither FAMS nor IPSBs: \$3 billion.

We have omitted opportunity and other secondary costs associated with security measures, such as increased passenger wait times at screening checkpoints and reduced passenger experience. These can delay some passengers, where waiting in security lines is an important indicator of passenger experience (Gkritza, Niemeier, & Mannering, 2006). In addition, visible physical security measures directed at terrorism can enhance fear and anxiety (Grosskopf, 2006). Ultimately, such delays and anxiety can deter many from flying at all. The omission of these opportunity costs biases the calculations toward finding that measures are cost-effective and that decisions are not risk-averse.

Consequences of a Successful Hijacking

The losses when an aircraft is successfully hijacked and flown into a target are considerable, particularly when one includes follow-on or secondary economic costs and social disruption. A 2005 RAND study hypothesized that the downing of an airliner by a shoulder-fired missile would lead to a total loss of more than $15 billion (Chow et al., 2005). The attack on the Pentagon on 9/11 caused up to $10 billion in losses counting physical damage, loss of life, and indirect losses such as social and business disruptions (Mueller & Stewart, 2011a, 2011b).

The September 11, 2001 attack directly resulted in the deaths of nearly 3,000 people. Following the widely applied value of statistical life (VSL) approach, a report for the DHS concluded that the best cost estimate for homeland security analysis is about $6.5 million in 2010 dollars (Robinson et al., 2010). Most VSL studies have focused on relatively common risks (e.g., workplace or motor vehicle accidents), and Robinson et al. (2010) suggested that more involuntary, uncontrollable, and dread risks may be assigned a higher VSL. Such a process would essentially add into the analysis much of the substantial indirect and ancillary costs associated with a terrorist event. Our analysis uses the lower figure of $6.5 million per life saved and then adds the other costs to this figure. However, the basic point, that people often effectively place a higher value on a life lost to terrorism than on one lost to more mundane and less sensational hazards, should be kept in mind.

Using a VSL of $6.5 million leads to a loss of approximately $20 billion arising from 3,000 fatalities. In addition, 9/11 caused approximately $30 billion in physical damage including rescue and clean-up costs (Bram, Orr, & Rapaport, 2002). Indirect costs were even more substantial. Thus, the International Monetary Fund estimated that the 9/11 attacks cost the U.S. economy up to 0.7 percent in lost GDP ($100 billion in 2010 dollars, adjusting for inflation) in that year alone, while others have estimated that associated business costs and loss of tourism cost the U.S. economy $190 billion over three years (Hook, 2008). Blomberg and Rose (2009) estimated that the impact on the U.S. economy of the 9/11 attacks ranged from 0.3 to 1 percent of GDP, or $50 to $150 billion in 2010 to 2011 dollars. An upper bound estimate of the losses of 9/11 might approach $200 billion—or $100 billion for a single aircraft, as most losses arose from the devastating attacks on the World Trade Center by two separate aircraft (Mueller & Stewart, 2011a).

The $10 billion in losses from the 9/11 attack on the Pentagon would be a plausible lower value—hence $L_1 = \$10$ billion. Moreover, $L_3 = \$100$ billion in losses, equivalent to the 9/11 losses from a single aircraft, is a plausible upper bound. A medium loss of $L_2 = \$50$ billion is reasonable; see Table 7. These consequences include direct, indirect, and induced losses.

Table 7. Probabilistic and loss data for hypothetical threats and losses.

Loss	Probability of loss $\Pr(L_i \mid T)$ (%)	Loss L_i
$i = 1$ Low	20	$10 billion
$i = 2$ Medium	40	$50 billion
$i = 3$ High	40	$100 billion

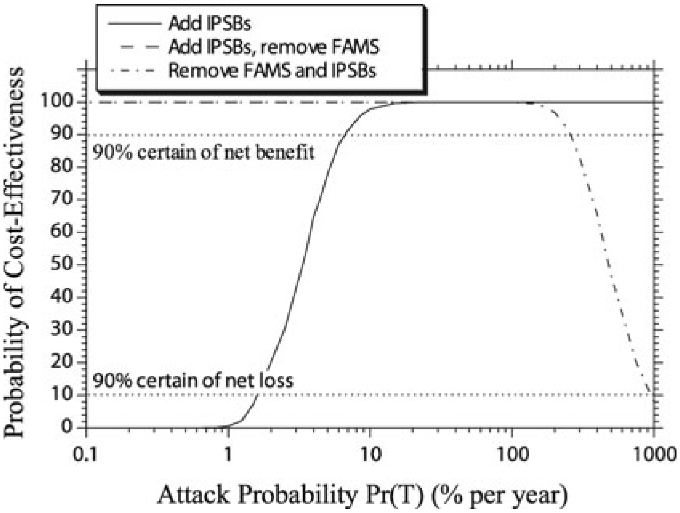


Figure 5. Probability of Cost-Effectiveness (Net Present Value Exceeds Zero).

RESULTS

Monte Carlo simulation was used to calculate the mean and 10th and 90th percentiles of net present value (NPV or net benefit) and expected utilities because losses and risk reduction are stochastic variables. Since the analysis considered only the costs and benefits for the following year, discounting of costs and benefits was not required. However, for a longer time period, results may be sensitive to discount rates used (Boardman et al., 2011) as is the relationship between discount rates and risk aversion (Snell, 2011). These issues are beyond the scope of the present paper.

It should be noted that there can be considerable additional costs for successfully disrupting a plot because the experience can heighten public averseness to travel (C_{add}). For example, a 1 percent drop in global passenger numbers for one year would reduce airline revenues by $5 billion (International Air Transport Association [IATA], 2011). This might particularly occur if a hijacking attempt were disrupted in an attempt to breach the hardened cockpit door (stage 3). These additional costs would be much higher if an airliner were shot down (stage 4): in this case, they might equal the lower bound of losses from a successful attack (such as the one on the Pentagon) of $C_{\text{add},4} = \$10$ billion. There would be no additional cost for a deterred plot (stage 1), and we assumed modest costs of $C_{\text{add},2} = \$500$ million for an attack that is foiled prior to boarding (stage 2).

Net Present Value

If $u(x) = x$, then equation (2) equates to a present value, and the NPV (or net benefit) is the present value for business as usual (existing measures) minus the present value for a policy scenario. This is a risk-neutral decision analysis. Figure 5 shows the probability that NPV > 0 for the three policy options. A reduction in risk may cause NPV > 0 but only if there is a reduction in security cost, and if the increase in expected losses is less than the reduction in costs.

Adding IPSBs produced a positive mean NPV for attack probabilities that exceeded 3 percent per year (or one attack every 33 years). However, to be 90 percent confident of a net benefit, attack probability needed to exceed 6 percent per year. A

Table 8. Probability that a policy option has higher utility than existing measures.

Attack probability Pr(T)	Include both IPSBs and FAMS				Include IPSBs, remove FAMS				Remove both FAMS and IPSBs			
	$\gamma = 0$	$\gamma = 2$	$\gamma = 5$	$\gamma = 10$	$\gamma = 0$	$\gamma = 2$	$\gamma = 5$	$\gamma = 10$	$\gamma = 0$	$\gamma = 2$	$\gamma = 5$	$\gamma = 10$
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	96%	8%	3%
50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	41%	4%
10%	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	5%
5%	80%	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	8%
1%	1%	23%	98%	100%	100%	100%	100%	100%	100%	100%	100%	52%
0.5%	0%	2%	88%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.1%	0%	0%	7%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.01%	0%	0%	0%	90%	100%	100%	100%	100%	100%	100%	100%	100%
0.001%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%
0.0001%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%

policy option that added IPSBs and removed FAMS produced higher net benefits. In this case, NPV was positive and probability of cost-effectiveness was 100 percent for all attack probabilities no matter how small. This arose because risk reduction was 0.8 percent higher than existing measures (see Table 5), and at substantially reduced cost ($980 million). The break-even analysis showed that attack probability needed to exceed 260 percent or 2.6 attacks per year for 90 percent surety that retaining FAMS was cost-effective. Such high attack probabilities are scarcely being observed, strongly suggesting that FAMS fails a cost-benefit assessment.

Expected Utility and Risk Aversion

Expected utilities were calculated for the three policy options and existing measures (business as usual) $\mathrm{E}_{\mathrm{NO}}[u]$ for attack probabilities of 0.0001 to 100 percent per year, and $L_{\max} = \$104{,}020$ (maximum $C_{\text{security}} + L_3$). A security measure was the preferred policy option if its expected utility exceeded $\mathrm{E}_{\mathrm{NO}}[u]$. Table 8 shows the probability that a policy option would be preferred for various attack probabilities and levels of risk aversion. A risk-neutral or linear utility function ($\gamma = 0$) yielded the same results as an NPV assessment. However, as degree of risk aversion increased ($\gamma > 0$), there was higher likelihood that adding IPSBs would be the preferred option even as attack probability decreased. Hence, for an extreme degree of risk aversion ($\gamma = 10$, see Figure 2), the security measure was 90 percent likely to be efficient for attack probabilities as low as 0.01 percent per year. This is probably understandable given the costs for IPSBs are minor at $20 million per year.

A policy of including IPSBs in the array of security measures while excluding FAMS was always the preferred policy option irrespective of the degree of risk aversion, as a measure that increases risk reduction at lower cost should always be preferred.

Excluding both FAMS and IPSBs from the array of security measures was found to lower risk reduction marginally, but at a billion dollar saving—almost all of it, of course, coming from the expensive FAMS program. A risk-neutral analysis found this policy option to be preferred over existing measures for all attack probabilities. However, a very risk-averse decisionmaker ($\gamma = 10$) would be 48 percent likely to prefer to retain FAMS even if the attack probability is 1 percent. This implies that the decisionmaker will be indifferent in choosing between a certain $50 billion loss and a lottery with 99.4 percent probability of zero loss and 0.6 percent chance of a $104,020 million loss. It follows that a loss of zero and a loss of tens of billions of dollars are nearly identically preferred—this is as extreme a case of risk aversion as possible ($\gamma = 10$), since $u(x) = 0.999$ for all costs x up to $30 billion.

In other words, when decisionmakers are risk-averse, they prefer a guaranteed large loss even though the probability of even larger losses is very small. Experience would suggest that few, if any, government agencies, such as the U.S. Nuclear Regulatory Commission or Environmental Protection Agency, exhibit anywhere near this level of risk aversion in their public decisionmaking (Ball & Floyd, 1998; Stewart, Ellingwood, & Mueller, 2011). However, if the likelihood of a terrorist airliner hijacking is less than 0.5 percent per year, or one attack every 200 years, even a significantly risk-averse decisionmakers would prefer to remove FAMS.

The analysis herein is a comparative analysis, so while the expected utilities would differ for other utility functions, the trends would be very similar to those shown above.

Sensitivity Analysis

Note that the results change for different input variables, but the trends are still the same. When the likelihood of large losses was increased to 50 percent (average loss is $75 billion), the break-even attack probabilities changed from 3 to 2.5 percent and 260 to 370 percent, for including both IPSBs and FAMS and for removing both FAMS and IPSBs, respectively. The probability that a policy option would be preferred based on expected utility changed by no more than 10 percent.

When the additional costs of a foiled attack were ignored ($C_{\text{add}} = 0$), the break-even attack probabilities increased from 3 to 4 percent and 260 to 550 percent, for adding IPSBs and for removing FAMS and IPSBs, respectively. The probability that a policy option would be preferred based on expected utility (Table 8) changed by less than 5 percent.

When we halved the deterrent rates of existing measures except for FAMS and IPSBs, then the mean additional risk reduction by adding IPSBs more than doubled to 2 percent and the attack probability needed to exceed only 1 percent per year for IPSBs to be cost-effective. Risk reduction was reduced by 1 percent when FAMS and IPSBs were removed, and the break-even attack probability was reduced to 1.7 attacks per year.

As noted, we have erred on the conservative side by selecting low rates of disruption for passengers and flight crew. When these are increased as in Tables 4 to 7, 30, and 50 percent (low, mid, and high), the break-even attack probabilities increase from 3 to 4 percent and 260 to 590 percent, for adding IPSBs and for removing both FAMS and IPSBs, respectively. Or if we assume that flight deck crew (and not just FFDOs) will actively resist any intrusion to the flight deck, then rates of disruption increase to 15, 30, and 50 percent (low, mid, and high). Break-even attack probabilities would then need to exceed 490 percent for FAMS to be cost-effective. The sensitivity analyses above show that attack probabilities have to be very high indeed for FAMS to pass a cost-benefit assessment.

CONCLUSIONS

These results strongly suggest that DHS decisionmakers are not following robust risk assessment methodology. If they were, low-cost solutions that are easily deployed and effective would be the first to be implemented. But it is not simply that the DHS is risk-averse. Its decisions cannot be supported even with the most risk-averse utility functions possible. This observation is supported by a 2010 report of a committee of the U.S. National Academy of Sciences (NRC, 2010). The committee could not find “any DHS risk analysis capabilities and methods” adequate for supporting the decisions made, and noted that “little effective attention” was paid to “fundamental” issues (p. 2). They were (with one exception) never shown “any document” that could explain “exactly how the risk analyses are conducted,” and they looked over reports in which it was not clear "what problem is being addressed" (p. 64). Since it does not seem to follow any well-accepted risk assessment methodology, DHS should not claim that its deliberations are "risk-based" when the evidence suggests otherwise.

A key problem in much homeland security analysis is the tendency to take a selective approach to risk assessment, focusing almost exclusively on imagining hazard scenarios (mostly rather extreme ones) and then analyzing the prospective consequences. There is relative neglect of several steps that are crucial for risk assessment to have any real credibility:

- Establishing and trying to quantify threat likelihood.
- Evaluating risks.
- Setting risk acceptance criteria.
- Establishing how much risk is likely to be reduced as a result of new security measures.

This paper shows how these steps can be used in a security risk analysis framework. The framework also serves to illustrate some important aspects of risk aversion for public decisionmaking, and the findings are robust to changes in parameter values. We have used well-known and accepted utility theory, and while the methods are not novel, the application to aviation security measures has not been attempted previously. The methods can be applied to other counterterrorism expenditures, such as airport security screening, infrastructure protection, and policing. Moreover, if public policymakers make decisions that might not be supported by a quantitative decision analysis, their degree of risk averseness needs to be quantified, and compared with other public policy decisions. This would make the trade-offs more transparent and highlight the degree to which risk aversion is excessive or justified.

In this paper, risk reductions were estimated for each layer of security designed to prevent commercial airliners from being commandeered by terrorists, kept under control for some time, and then crashed into specific targets. The total risk reduction from existing security measures is a high 98 to 99 percent. Policy options to reduce the remaining risk included adding IPSBs to aircraft and removing FAMS. It was found that attack probabilities would need to exceed 260 percent or 2.6 attacks per year to be 90 percent sure that FAMS is cost-effective. A policy option of "business as usual" is optimal for lower attack probabilities because the large cost of FAMS fails to be offset by its benefit. On the other hand, IPSBs have more than 90 percent chance of being cost-effective even if attack probabilities are as low as 6 percent per year.

It was also shown that the level of risk averseness needed to justify current aviation security expenditures is considerable. Even applying estimates that generally bias the case in favor of finding airline security measures to be cost-effective, it seems likely that far too much is being spent to address the problem of airline hijacking. For example, removing FAMS will lower risk reduction negligibly at most while saving a billion dollars a year. Many spending reductions could likely be made with little or no consequent reduction in security. Further research may focus on collecting and analyzing performance data on the effectiveness and the interaction of other specific security measures while also including opportunity costs in the decision analysis.

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APPENDIX

$$\Pr(\text{foiled in flight}) = 1 - \left\{ \begin{array}{l} [1 - \Pr(\text{foiled by passengers})] \\ \times[1 - \Pr(\text{foiled by flight crew})] \\ \times[1 - \Pr(\text{foiled by LEO})] \end{array} \right\} \tag{A.1}$$

Note: LEO = law enforcement officer.

Existing Security Measures

$$\Pr(\text{deterred}) = \left\{ \begin{array}{l} [1 - \Pr(\text{deterred by pre} - \text{ boarding security measures})] \\ \times[1 - \Pr(\text{deterred by passenger and flight crew resistance})] \\ \times[1 - \Pr(\text{deterred by hardened cockpit door})] \\ \times[1 - \Pr(\text{deterred by FAMS})] \\ \times[1 - \Pr(\text{deterred by LEO})] \\ \times[1 - \Pr(\text{deterred by flight deck resistance})] \\ \times[1 - \Pr(\text{deterred by anti} - \text{aircraft measures})] \end{array} \right\} \tag{A.2}$$

$$\begin{aligned} &\Pr(\text{failed to commandeer airliner}) \\ &= 1 - \left\{ \begin{array}{l} [1 - \Pr(\text{foiled in flight})] \\ \times [1 - \Pr(\text{foiled by door} \,|\text{FAMS})] \\ \times [1 - \Pr(\text{foiled by flight deck resistance})] \end{array} \right\} \end{aligned} \tag{A.3}$$

Pr(foiled by flight deck resistance) is the probability that pilots and Federal Flight Deck Officers (FFDOs) will successfully resist an intrusion into the flight deck either by the use of personal firearms or, if not armed, by other means at their disposal. Pr(foiled by door | FAMS) is the sum of the disruption rate without Federal Air Marshal Service (FAMS) and the incremental increase in disruption rates due to having FAMS on the flight. Hence,

$$\begin{aligned} \Pr(\text{foiled by door} \,|\text{FAMS}) = {} & \Pr\left(\text{foiled by door} \,\middle|\text{no FAMS on board}\right) \\ & + \left[\begin{array}{l} \Pr\left(\text{foiled by door} \,\middle|\text{FAMS on board}\right) \\ - \Pr\left(\text{foiled by door} \,\middle|\text{no FAMS on board}\right) \end{array} \right] \\ & \times \Pr(\text{FAMS on flight}) \end{aligned} \tag{A.4}$$

Pr(foiled by door | no FAMS on board) is the probability that the cockpit door is closed and locked before a hijacker can “rush” it during a door transition. This requires the flight and cockpit crew to react quickly to a threat, and since there is no Improvised Physical Secondary Barrier (IPSB) installed, then airlines will rely either on (less effective) galley trolleys to block access to the flight deck or on other instituted procedures during door transition. Pr(foiled by door | FAMS on board) is the probability that FAMS will react quickly enough to detain or slow a hijacker, allowing the hardened cockpit door to be closed and locked.

1. Include both IPSBs and FAMS

$$\Pr(\text{deterred}\,|\text{IPSB}) = [1 - \Pr(\text{deterred}))] \times [1 - \Pr(\text{deterred by IPSB})] \tag{A.5}$$

$$\begin{aligned}&\Pr(\text{failed to commandeer airliner})\\ &= 1 - \left\{\begin{array}{l}[1 - \Pr(\text{foiled in flight})]\\ \times[1 - \Pr(\text{foiled by IPSB })]\\ \times[1 - \Pr\left(\text{foiled by door}\,\middle|\text{IPSB fails}\,|\text{FAMS }\right)]\\ \times[1 - \Pr(\text{foiled by flight deck resistance})]\end{array}\right\}\end{aligned} \tag{A.6}$$

Pr(foiled by IPSB) is the probability that the IPSB is deployed and will function as intended and delay a hijacker sufficiently to allow the cockpit door to be closed.

$$\begin{aligned}&\Pr\left(\text{foiled by door}\,\middle|\text{IPSB fails}\,|\text{FAMS }\right)\\ &= \Pr\left(\text{foiled by door}\,\middle|\text{IPSB fails}\,|\text{no FAMS on board}\right)\\ &\quad+\begin{bmatrix}\Pr\left(\text{foiled by door}\,\middle|\text{IPSB fails}\,|\text{FAMS on board}\right)\\ -\Pr\left(\text{foiled by door}\,\middle|\text{IPSB fails}\,|\text{no FAMS on board}\right)\end{bmatrix} \times \Pr(\text{FAMS on flight})\end{aligned} \tag{A.7}$$

2. Include IPSBs, remove FAMS

$$\Pr(\text{deterred}\,|\text{IPSB, no FAMS}) = 1 - \Pr(\text{deterred}\,|\text{IPSB})/1 - \Pr(\text{deterred by FAMS}) \tag{A.8}$$

$$\begin{aligned}&\Pr(\text{failed to commandeer airliner})\\ &= 1 - \left\{\begin{array}{l}[1 - \Pr(\text{foiled in flight})]\\ \times[1 - \Pr(\text{foiled by IPSB})]\\ \times[1 - \Pr(\text{foiled by flight deck resistance})]\\ \times[1 - \Pr\left(\text{foiled by door}\,\middle|\text{IPSB fails}\,\middle|\text{no FAMS on board }\right)]\end{array}\right\}\end{aligned} \tag{A.9}$$

3. Remove both FAMS and IPSBs

$$\Pr(\text{deterred}\,|\text{no FAMS}) = 1 - \Pr(\text{deterred})/1 - \Pr(\text{deterred by FAMS}) \tag{A.10}$$

$$\begin{aligned}&\Pr(\text{failed to commandeer airliner})\\ &= 1 - \left\{\begin{array}{l}[1 - \Pr(\text{foiled in flight})]\\ \times[1 - \Pr\left(\text{foiled by door}\,\middle|\text{no IPSB and no FAMS}\right)]\\ \times[1 - \Pr(\text{foiled by flight deck resistance})]\end{array}\right\}\end{aligned} \tag{A.11}$$