Should We Protect Commercial Airplanes Against Surface-to-Air Missile Attacks by Terrorists?

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This paper describes a decision tree analysis to assess the cost-effectiveness of MANPADS (Man-Portable Air Defense Systems) countermeasures. These countermeasures are electronic devices that can be installed on commercial airplanes to detect and deflect surface-to-air missiles (SAMs) fired by terrorists. The model considers a terrorist attempt to shoot down a commercial airplane with a heat-seeking SAM, and it evaluates the decision to install countermeasures, taking into account alternative modes of attack, probabilities of success, and consequences to the economy. All model variables were fully parameterized, using reasonable ranges based on open-source literature. Not surprisingly, the probability of an attack, the consequences of an attack to the economy, and the cost of countermeasures are the most important parameters. Surprisingly, some of the hotly disputed parameters, such as the probability of an airplane surviving a successful hit or the probability of a false alarm, have very little impact on the results. The analysis suggests that MANPADS countermeasures installed on planes can be cost-effective if the probability of such an attack is large (greater than about 0.40 in ten years), the economic losses are large (greater than about $75 billion), and the countermeasures are relatively inexpensive (smaller than about $15 billion). An economic analysis conducted as part of this analysis showed that the economic impacts can be as large as $250 billion, thus making countermeasures a possibly cost-effective option. More research is needed to determine the real costs of MANPADS countermeasures and how terrorists may shift their tactics, once countermeasures are installed.

Key words: terrorism risk; aviation system attacks; surface-to-air missiles; MANPADS; risk analysis; MANPADS countermeasures
History: Received on April 23, 2006. Accepted by Robert Clemen on June 21, 2006 after 2 revisions.

1. Introduction

The threat of attacks on U.S. and other western commercial aircraft using man-portable air defense systems (MANPADS)—heat-seeking or laser-guided surface-to-air missiles (SAMs)—has been recognized widely since 2001 (see for instance Bolkcom and Elias 2006, GAO 2004a, Shanker 2002, Phelps 2003, Hunter 2002).[1] In recent years, there have been publicized MANPADS attacks on large civilian aircraft, in Baghdad, Iraq (*Space Daily* 2003) and Mombasa, Kenya (*Jane's Intelligence Review* 2003)[2] which heightened fears of such attacks in the United States or over-

seas. It is estimated that at least 4,000 to 5,000 of these missiles may be accessible to anti-Western terrorist organizations (Bolkcom and Elias 2006).

The United States has engaged in efforts to purchase and destroy missiles in Iraq, Russia, and other regions (GAO 2005, Bolkcom and Elias 2006).[3] While this effort has been fairly successful, it is countered by additional production and distribution of new missiles, for example, by China (O'Sullivan 2004) and by the lack of international treaty regulations of missile trade.

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[1] There were earlier warnings as well. See for instance Marvin B. Schaffer, "Concerns About Terrorists With Manportable SAMS," *RAND Corporation Reports*, October 1993.

[2] The 2003 Baghdad DHL A300 cargo jet was attacked with a Russian-made SA-14 MANPADS missile, and resulted in a wing fuel tank fire, loss of all three hydraulic systems, and a crash landing

with no injuries at the Baghdad International Airport. The Mombasa attack was directed at an Israeli Arkia charter jet, but the missile(s) did not hit the target.

[3] See, for instance United States Department of State Fact Sheet, "The MANPADS Menace: Combating the Threat to Global Aviation from Man-Portable Air Defense Systems." http://www.state.gov/t/pm/rls/fs/53558.htm.

In addition to MANPADS, other threats to the aviation system must be addressed, including concerns that terrorists might use, for example, large caliber sniper rifles, mortars or rocket-propelled grenades (RPGs) (see Grau 1998, Violence Policy Center 2002, Bennett 2003, O'Sullivan 2004, Chow et al. 2005) to attack airborne planes and/or grounded aircraft and airport facilities. Not only are passengers, personnel, and airline infrastructure threatened, but also the health of the entire airline industry, which is only now recovering from long-term economic damage sustained in the aftermath of the Al Qaeda attacks on September 11, 2001. In particular, there have been significant concerns by policy makers that missile attacks on airplanes, possibly at multiple locations and repeated over time, would be a devastating blow to the industry and could cause massive related economic consequences to travel, tourism, and related industries (GAO 2004b).

There are effective electronic countermeasure systems capable of being deployed against most infrared-guided missiles. These countermeasures have up to now been used primarily on military aircraft and consist of missile detection and tracking devices coupled with either "smart" flares ejected from the plane to confuse the missile, or infrared jammers that actively interfere with the missile homing seeker.[4] El-Al has recently installed countermeasures on its fleet of commercial aircraft.

In 2004 the United States Department of Homeland Security (DHS) initiated a $100 million program to develop directed infrared countermeasures (DIRCMs) that jam the heat seeking device of a MANPAD and deflect its course away from the airplane. This program is in support of a pending decision by Congress on whether or not to request that some or all U.S. commercial airliners install them. At present, there are no effective countermeasures against *non*-infrared MANPADS, such as laser beam-riders (LBR),[5] command line-of-sight (CLOS) mis-

siles, or against other weapons that might damage or destroy an aircraft in the air or on the ground.

In addition to countermeasures intended to prevent attacks, other measures can increase the likelihood that an airliner might survive a "successful" hit. These survival countermeasures include hardening the engines, fuselage, or cockpit; improving redundancies in key systems; installing fuel tank fire-suppression systems; and providing pilots with better training on how to safely land attack-damaged planes. At this writing, current DHS initiatives are concentrating primarily on preventing infrared-guided MANPADS missile hits via aircraft-based DIRCM systems, and not on survivability countermeasures.

The analysis presented in this article was initiated in 2004 as part of a series of terrorism risk analyses conducted by the Center for Risk and Economic Analysis of Terrorism Events (CREATE), the first University Center of Excellence sponsored by the Department of Homeland Security, at the University of Southern California. During one of the initial planning meetings, the MANPADS threat was identified as a significant issue by the director of the DHS office of research and development. CREATE staff agreed to conduct a decision analysis of this issue and contacted the Counter-MANPADS System Program Office (SPO) to offer its support. A decision was made to conduct this analysis independently from the SPO with funding by CREATE to ensure that the results would not be considered as being tainted by the interests of the SPO, which is perceived by some as promoting MANPADS countermeasures. Nevertheless, we considered the SPO and its congressional counterparts as the key clients of this effort, and we interacted with them at several times during the analysis.

The purpose of the analysis presented in this paper is to contribute to the ongoing deliberations about the cost effectiveness of civilian aircraft-deployed DIRCMs. Some analysts and some airline officials have already concluded that they are not cost-effective (see, for example, Chow et al. 2005), because of the substantial capital and operations and maintenance costs relative to the potential losses of lives and

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[4] Generally referred to as directed infrared counter-measures (DIRCM).

[5] Pakistan, for instance, produces an effective laser beam-rider MANPADS, which was modeled after the Swedish RBS-70 missile, against which infrared countermeasures are ineffective. There are concerns that radical Islamic members of the Pakistani Army are

sympathetic to Al Qaeda and similar terrorist groups, and might be a source for non-IR, LBR MANPADS weapons, training, or recruitment.

Figure 1   MANPADS Decision Tree
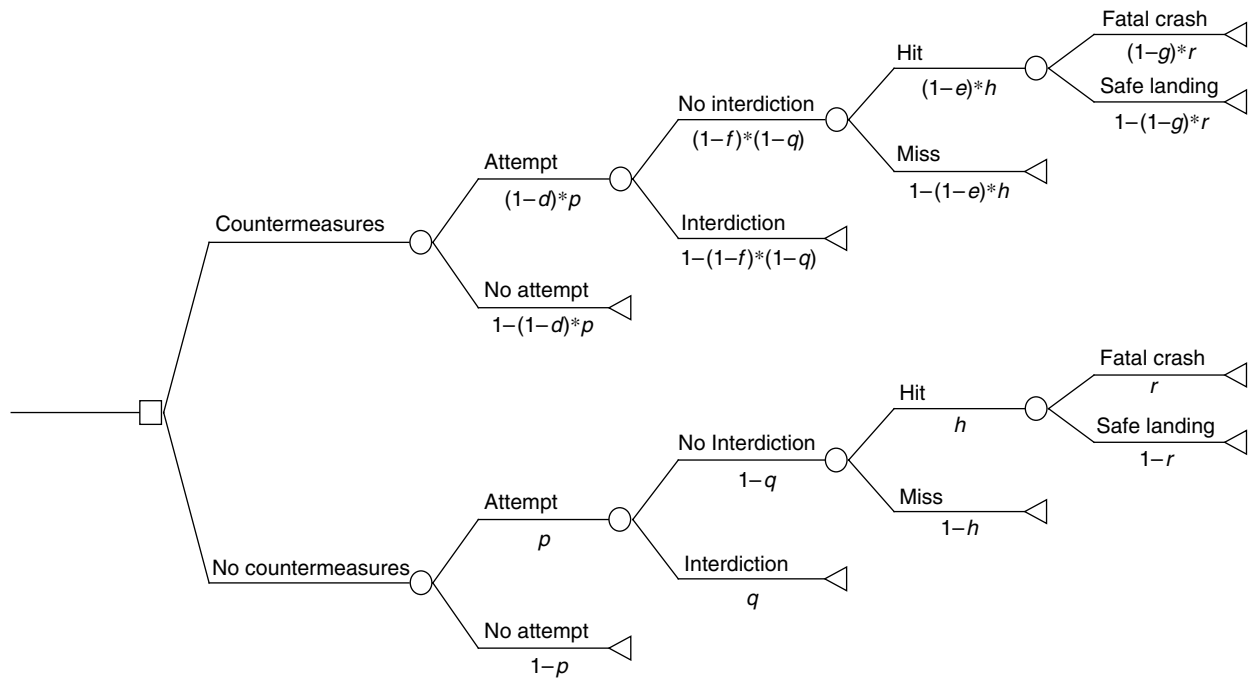
the losses to the economy. Others, especially political representatives, argue that the country should do far more to protect the public from an imminent threat to reduce the risk of another major disaster involving the airline industry.[6]

To explore some of these issues and trade-offs, this analysis focuses on a scenario of a single terrorist attack using a heat-seeking SAM to attempt to shoot down a large plane in the United States. Using decision tree analysis, we explore the effects of implementing countermeasures to reduce the risk of a successful attack. The idea of this analysis was not to focus on the specific numerical probabilities or consequences, but to provide a very flexible tool for decision makers to explore the impact of alternative assumptions on the cost-effectiveness of installing MANPADS countermeasures.

In the next section of this paper, we show the basic decision tree used throughout this analysis. This tree

was built using an Excel add-in called TreePlan (Decision Support Services 2005). All probabilities and consequences in this tree are parameterized. They are controlled through a user-friendly Visual Basic interface that shows both numerically and graphically how the changes in the inputs (probabilities, consequences, and tradeoffs) affect the outputs (equivalent expected costs of the MANPADS risk with or without countermeasures). Additional sensitivity analyses were performed using the software Treeage Pro, by Treeage Software, Inc. (2005). This software allows users to explore one-, two-, and even three-way sensitivity analyses to determine the impacts of input changes on the analysis outputs.

2. Decision Tree and Preliminary Sensitivity Analysis
Figure 1 shows the decision tree used throughout this analysis. The key decision is whether or not to install countermeasures. At this point, it is not important to consider exactly what type of countermeasures to install, because the effects of the countermeasure are parameterized in terms of the deterrence probability and of the effectiveness in avoiding a hit or

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[6] See, for instance, Shoulder-Fired Missile Reduction Act of 206, HR 5333, at http://fas.org/asmp/resources/govern/109th/HR5333ith.pdf, and "Boxer Urges Chertoff to Protect American Aircraft from the Threat of Shoulder-Fired Missiles," Press Release of Senator Barbara Boxer (March 26, 2006), accessed at http://boxer.senate.gov/news/releases/record.cfm?id=253217.

Table 1   Base Case and Ranges of Probabilities and Effectiveness Parameters

		Min	Base	Max
Probabilities				
p	Attempted attack in 10 years	0.00	0.50	1.00
q	Interdiction | attempt	0.00	0.00	0.25
h	Hit | attack, no countermeasures	0.50	0.80	1.00
r	Crash | hit	0.00	0.25	0.50
Effectiveness of countermeasures				
d	Deterrence effectiveness	0.00	0.50	1.00
f	Interdiction effectiveness	0.00	0.00	0.25
e	Diversion/destruction effectiveness	0.50	0.80	1.00
g	Crash reduction effectiveness	0.00	0.00	1.00

fatal crash. This decision has costs and these costs are parameterized as well, using information from various sources, including the recent RAND report (Chow et al. 2005). Table 1 shows the base case probabilities and their ranges as used in this analysis. The ranges are wide and include all parameter values that are considered reasonable by experts in this area. The base case values are our best guesses from information in the open source literature. Better information about some of these parameters exists, but some of this information is sensitive or classified.

Considering the decision not to install countermeasures (lower part of Figure 1), the first event node concerns whether terrorists will attempt an attack on airplanes in the United States. This probability (p) is very hard to assess, depending on vague and ambiguous intelligence information. In this analysis, we consider a ten-year time horizon and vary the probability of an attack through the full range from 0 to 1. The base case of $p = 0.50$ arises from the facts that many MANPADS weapons are currently in terrorists' hands and that a market for these weapons exists in the United States, as suggested by recent open-source reports. To demonstrate the methodology, we focus on a single attack, although we will discuss generalizations to multiple and repeated attacks in the conclusion.

The next node is the probability that an attempted attack will be interdicted (q)—for example, by citizens alerting the police about a suspicious activity near the perimeter of the airport. MANPADS are capable of hitting targets at altitudes of up to 15,000 feet, which makes them effective at radiuses of 50 miles or more from most airports. With such

a large radius perimeter control is largely ineffective. Therefore, we assume that the interdiction probability is zero in the base case. Future applications of this model can use this parameterized probability to explore the cost-effectiveness of perimeter control countermeasures—particularly for shorter range, non-MANPADS weapons such as large caliber rifles and rocket propelled grenades (RPGs).

If the attack is not interdicted on the ground and a MANPADS missile is successfully fired, there is a chance (h) that the missile will hit the aircraft. The range of this parameter is known, but classified. Using open-source literature, we use a base case of 0.80 and a range from 0.50 to 1.0 for sensitivity analysis. The lower part of this range is not set to zero, since it can be assumed that these missiles are quite effective, especially at medium range. Finally, depending on how and where the plane is hit, there is a chance that the pilots manage to land the plane safely or not (r). There is some evidence that planes can survive a MANPADS hit, like the case of the Airbus A300 that survived the hit in Baghdad in 2003, but the actual chance of survival is highly contested. We used a probability of 0.25 of a crash, given a hit with a range of 0 to 0.50 to reflect these differences in opinion.

The event nodes are identical for the decision to install countermeasures, but the countermeasures will reduce several probabilities. First, installing countermeasures may deter terrorists from launching this type of attack. This deterrence effect is parameterized by a factor d. If d is large (100%), the terrorists are completely deterred; if d is zero, they are not deterred at all. In this analysis we varied the deterrence probability from 0 to 100%, with a base case of 50%. Next is the effectiveness of perimeter control countermeasures (f), the effectiveness of increasing the probability of interdiction of a missile attack on an airplane. Parameter f is currently only a placeholder and set to 0% in the base case.

Any electronic countermeasures on the aircraft are designed to deflect the missile from hitting the plane. The deflection effectiveness is expressed in the parameter e. If $e = 100\%$, the countermeasures are 100% effective in deflecting a SAM. Open-source data suggest a high effectiveness. Because countermeasures with low effectiveness would never be considered,

our analysis uses a range of 50% to 100% for this parameter, with a base case of 80%.

Another parameter is g, the effectiveness of reducing the crash probability, given a hit. This parameter depends on measures to harden the airplane or to improve pilot training. It is set at zero in the base case. Thus, the only non-zero effectiveness parameters are d (deterrence effectiveness) and e (deflection effectiveness).

The decision tree in Figure 1 summarizes the major decisions and events. In addition, we need to describe the consequences of the attack at each end node of the tree. We considered five consequences:

1. Loss of lives due to a crash (LL)
2. Cost of the plane (CP)
3. Economic losses to the airline industry and the overall economy (EL)
4. Number of false alarms (FA)
5. Costs of the countermeasures (CC)

As with the probabilities, we used a highly parameterized approach and constructed the model to cover a very wide range of losses and costs. Table 2 summarizes the base case values and ranges.

We used a range of losses of life between zero and 400 deaths (base case = 200), a cost of the loss of the airplane between zero and $500 million (base case = 200 million) and estimated losses to the airline industry and the overall U.S. economy at between zero and $500 billion (base case = $100 billion). The high end of the economic loss (EL) was motivated by recent analyses that estimated the costs of a 9/11-like attack on the airline industry. For example, in a study commissioned by CREATE, Gordon et al. (2006) estimate that these economic costs for the two years following the 9/11 attack were somewhere between $250 billion and $400 billion. Their estimate includes the cost of an initial shutdown and a subsequent drop in passenger

volume of about 20% in the first year and 10% in the second year. Santos and Haimes (2004) estimated that a drop of 10% in airline passenger volume cost the economy up to $40 billion/year.

Unsuccessful MANPADS attacks that hit the plane but result in safe landings and complete misses also have economic costs, because they may create fear of future attacks and subsequently reduced passenger traffic. For hits with safe landings, we used a loss reduction parameter a with base case 25% and a range from 0% of the economic costs of a hit and fatal crash to 50%. For misses, we used a loss reduction parameter b with a base case of 10% and a range from 0% to 25%.

Estimates of the aggregate costs of DIRCM countermeasures are controversial. The RAND Corporation estimates a capital cost of $10 billion and $2.5 billion annual operations and maintenance costs, assuming that all large commercial airliners (5,000 passenger and 1,500 cargo airplanes) are equipped with countermeasures. This would lead to an (undiscounted) $35 billion life-cycle cost over ten years. Airline industry officials quote much higher costs of up to $100 billion and promoters of MANPADS countermeasures quote much lower costs of $10 billion or less. To accommodate this range of opinions, we parameterized the ten year costs of the system at between $5 billion and $50 billion (base case = $10 billion).

False alarms are another source of costs, especially when they lead to the grounding of aircraft or closing of airports. There are no hard data on false alarms, although those associated with deployed military DIRCM countermeasure systems are likely to be far higher than could be tolerated by the commercial airline industry. Nevertheless, even with lower rates, false alarms will happen and their consequences will be highly dependent on the specific policies for responding to alarms, false or otherwise. We varied false alarms between 0 and 20 per year based on the understanding that countermeasures with larger false alarm rates would be unacceptable.

All consequences are in dollars, calculated for ten years, with the exception of lives lost and false alarms. The monetary value of a life (VOL) was set at $5 million for the base case with a range of $0 to $10 million. The monetary value of a false alarm (VOF) ranged from $0 per incident to $100 million, with

Table 2 Base Case Consequences and Ranges

Consequences		Min	Base	Max
LL	Fatalities | crash	0	200	400
CP	Cost of the plane (millions)	0	200	500
EL	Economic loss | fatal crash (billions)	0	100	500
a	Percent of loss | hit and safe landing (%)	0	25	50
b	Percent of loss | miss (%)	0	10	25
FA	Number of false alarms/year	0	10	20
CC	Cost of countermeasures (billions)	5	10	50

$10 million for the base case, reflecting the uncertain consequences of a false alarm.

With this information, we can calculate an overall equivalent cost (EC_j) at each end node of the decision tree as the weighted sum of the five component costs:

$$EC_j = \sum c_i x_{ij},$$

where c_i is the equivalent cost of one unit of consequence i, and x_{ij} is the ith consequence for end node j in the decision tree.

We considered discounting the equivalent costs. This would involve separate evaluations of MANPADS attacks for each of the possible time periods (from 1 to 10 years) as well as separate probability assessments for each of the ten time periods. While doing so does not pose any technical difficulties, it appears to be a technical detail that would scale the calculations for each alternative in a similar way, and therefore would add little if any insight. Thus, the results are presented in undiscounted ten-year costs.

Following the top branches of the decision tree in Figure 2, the base case equivalent cost (in billions) is

EC (Countermeasures, Attempt, No Interdiction, Hit, Fatal Crash)

$$= VOL * LL + CP + EL + CC + VOF * FA * 10$$

$$= 0.005 * 200 + 0.200 + 100 + 10 + 0.010 * 10 * 10$$

$$= \$112 \text{ billion.}$$

The multiple of 10 in the false alarm term is due to the ten-year time horizon.

Figure 2 shows the solved decision tree, using base case probabilities, consequences, and tradeoffs. At the root node of this tree, the expected equivalent costs are shown ($15 billion for countermeasures and $19 billion for no countermeasures), and the branch suggesting countermeasures shows a double slash, indicating that this is not the preferred path. The end nodes in this tree show the equivalent costs (in billions of dollars) associated with the corresponding path. For end nodes that involve the preferred decision (no countermeasures in the base case), the probabilities of arriving at these end nodes are also provided. These probabilities are simply the product of the probabilities of each preceding event branch.

When we initially presented the results in Figure 2 to members of organizations interested in the MANPADS issue, we encountered strong opposition. The results in Figure 2 suggest that MANPADS countermeasures are a good idea ($15 billion expected equivalent cost versus $19 billion with no countermea-

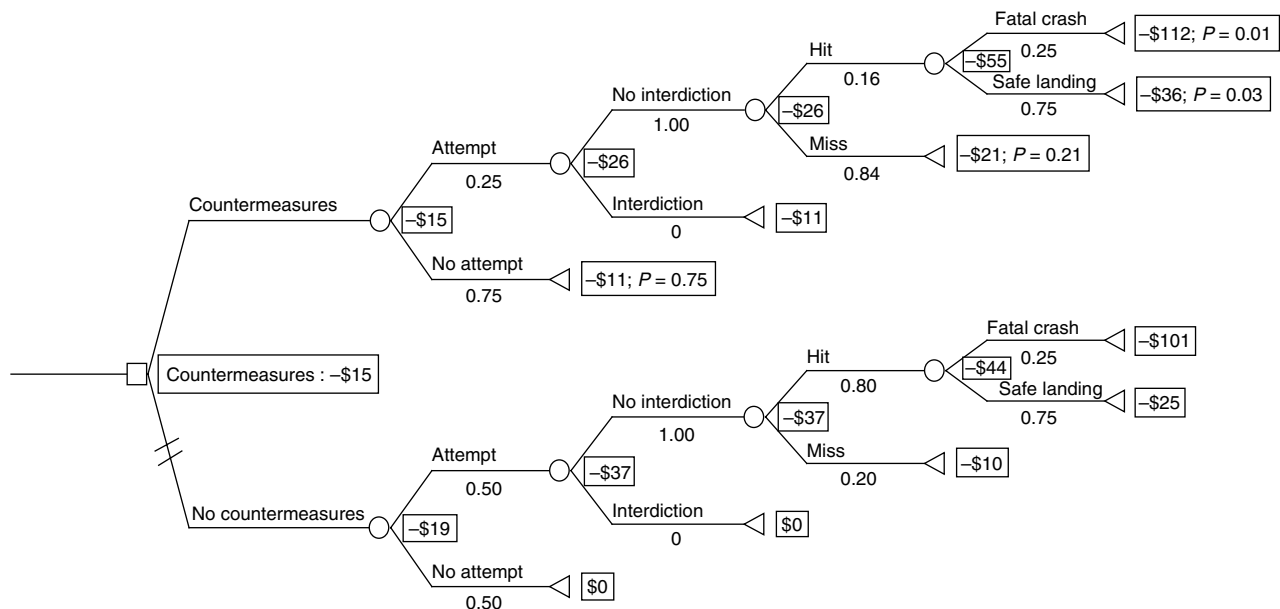**Figure 2   Solved Decision Tree with Base Case Values**

Figure 3   Inputs that Favor MANPADS Countermeasures

Inputs and ranges of the MANPADS model

Probabilities	Base Case	Slider Case	Min			Max	
Attempted attack in 10 years	0.50	0.50	0.00			1.00	
Interdiction|attempt	0.00	0.00	0.00			0.10	
Hit|attack	0.80	0.81	0.50			1.00	
Crash|hit	0.25	0.25	0.00			0.50	
Effectiveness of countermeasures							
Deterrence effectiveness	0.50	0.50	0.00			1.00	
Interdiction effectiveness	0.00	0.00	0.00			1.00	
Diversion/destruction effectiveness	0.80	0.80	0.00			1.00	
Crash reduction effectiveness	0.00	0.00	0.00			1.00	
Consequences							
Fatalities|crash	200	200	0			400	
Cost of the plane (millions)	200	200	0			500	
Economic loss|fatal crash (billions)	100	100	0			500	
Percent of loss|hit and safe landing	25%	25%	0%			50%	
Percent of loss|miss	10%	10%	0%			25%	
Number of false alarms/year	10	10	0			20	
Cost of countermeasures (billions)	10	10	5			50	
Tradeoffs							
Value of life (millions)	5	5	0			10	
Cost of a false alarm (millions)	10	10	0			100	

Expected costs of MANPADS

Outputs of manpads model

		Total	Crash	Econ loss	CM cost
Expected costs w/ countermeasures (millions)	**w/ CM**	$ 14,881	$ 14	$ 3,867	$ 11,000
Expected costs w/o countermeasures (millions)	**w/o CM**	$ 18,805	$ 137	$ 18,669	$ -
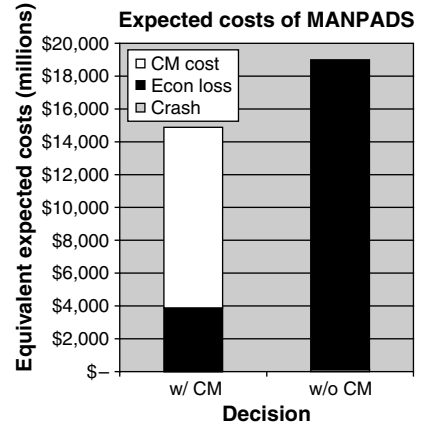
sures), thus provoking criticism from opponents to countermeasures. Similarly, when we presented opposite results favoring no countermeasures, we faced criticisms from groups favoring countermeasures. It was very difficult to convince the audience that our base case analysis was not meant to make a specific recommendation but was only a starting point for sensitivity analyses that would clarify the issues.

Eventually, we stopped presenting base case results and presented the analysis purely in terms of sensitivity analyses. We used displays that made it obvious that the parameters of the model could change, and we presented at least two different points of view. Figures 3 and 4 are two examples. Figure 3 favors countermeasures (lower equivalent costs of countermeasures), and Figure 4 favors no countermeasures (higher equivalent costs of countermeasure). The black bar segments in Figures 3 and 4 represent the expected economic loss, the white bar segments represents the cost of the countermeasures. Note that the grey bar, representing the equivalent expected cost of other consequences, can hardly be seen at the bottom of the two bars.

Most notably, the base case in Figure 3, which favors countermeasures, includes a 50% chance of an attempted MANPADS attack in the next ten years in

the United States and a $100 billion economic cost. A 50% chance of a MANPADS over the next ten years is high but is not considered unreasonable by some intelligence experts. An economic loss of $100 billion is high for a single MANPADS attack but possible for a multiple and repeated attack, which might create fears of flying similar to those created by the 9/11 attack. The case that favors *no* countermeasures posits a 25% chance of an attempt and $50 billion economic costs from an attack. These are considered reasonable lower bounds of the probability and consequences of a single MANPADS attack. Otherwise these two cases are identical at the base case values. As we will discuss later, these parameters are crucial in determining whether DIRCM countermeasures are cost-effective or not.

These figures also illustrate how the initial sensitivity analysis is performed. Without being too concerned about specific numbers, the decision tree probabilities and consequences are controlled by so-called "sliders," which can vary the parameters over a wide range. By moving these sliders on the screen, the decision maker can observe in real time how the graphically-displayed results change as the input parameters are varied across their ranges.

Figure 4   Inputs that Favor No Countermeasures

Inputs and ranges of the MANPADS model

Probabilities	Base Case	Slider Case	Min		Max	
Attempted attack in 10 years	0.50	0.50	0.00		1.00	
Interdiction|attempt	0.00	0.00	0.00		0.10	
Hit|attack	0.80	0.81	0.50		1.00	
Crash|hit	0.25	0.25	0.00		0.50	
Effectiveness of countermeasures						
Deterrence effectiveness	0.50	0.50	0.00		1.00	
Interdiction effectiveness	0.00	0.00	0.00		1.00	
Diversion/destruction effectiveness	0.80	0.80	0.00		1.00	
Crash reduction effectiveness	0.00	0.00	0.00		1.00	
Consequences						
Fatalities|crash	200	200	0		400	
Cost of the plane (millions)	200	200	0		500	
Economic loss|fatal crash (billions)	100	100	0		500	
Percent of loss|hit and safe landing	25%	25%	0%		50%	
Percent of loss|miss	10%	10%	0%		25%	
Number of false alarms/year	10	10	0		20	
Cost of countermeasures (billions)	10	10	5		50	
Tradeoffs						
Value of life (millions)	5	5	0		10	
Cost of a false alarm (millions)	10	10	0		100	

Outputs of manpads model

		Total	Crash	Econ loss	CM cost
Expected costs w/ countermeasures (millions)	w/ CM $	11,974	$ 7	$ 967	$ 11,000
Expected costs w/o countermeasures (millions)	w/o CM $	4,736	$ 68	$ 4,667	$ -
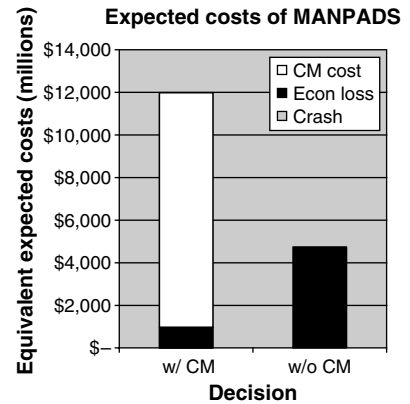
3.   Sensitivity Analyses

Although the slider interface is very user friendly, it does not cover all sensitivity analyses that one may wish to explore. In the following, we used the same decision tree model, but a different software tool (Treeage Pro) to run numerous sensitivity analyses.

First, we ran a *tornado analysis*, which shows the change in expected equivalent cost of the optimal decision (countermeasures versus not) as a function of changing each input variable through the range of numbers shown in Tables 1 and 2. The larger the horizontal bar in a tornado diagram, the more impact the input variable has on the expected equivalent cost. The vertical hash marks on the horizontal bars show the value of a variable at which the decision would switch from no countermeasures to countermeasures. To the left of the hash mark, countermeasures are preferred; to the right, no countermeasures are preferred. It is clear from Figure 5 that the probability of an attempt and the economic losses due to a hit and fatal crash are the most important input variables.

Figures 6 through 8 show one-way sensitivity analyses for economic loss EL due to a hit and crash (Figure 6), probability of an attempt p (Figure 7), and cost of countermeasures CC (Figure 8). The lines in Figures 6, 7, a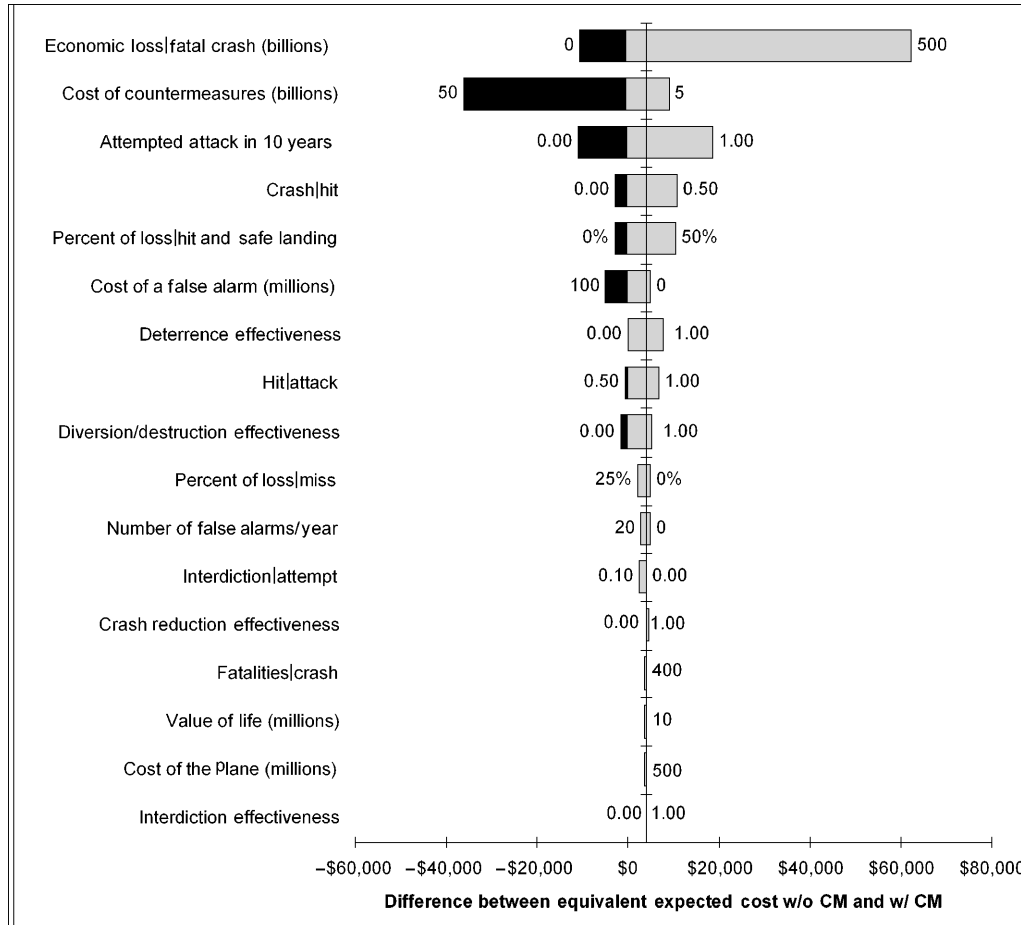nd 8 show the expected equivalent costs of using countermeasures versus not using countermeasures. In each graph, where the lines intersect represents the point at which countermeasures and no countermeasures have the same expected equivalent costs. For the purpose of these sensitivity analyses, all variables except the ones on the horizontal axes of Figures 6–8 were kept constant at the base-case values shown in Tables 1 and 2.

In short, these three sensitivity analyses show that countermeasures are preferred (lower expected equivalent cost) if economic losses are above $74.3 billion, if the probability of attack is larger than 37% in ten years, and if the cost of countermeasures is less than $13.8 billion, other parameters remaining at their base values.[7]

To explore the joint effects of the three most important variables, we conducted several sensitivity analyses varying two parameters at the same time. Figure 9 shows how the decision to deploy or not to deploy countermeasures changes as a function of the probability of an attempted attack and the economic losses of a hit and crash. The curve that separates the lower

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[7] To avoid giving the impression of false precision, we rounded off these break-even numbers in our communication with decision makers and in some places of this paper to $75 billion (economic loss), 0.40 (probability of an attempt), and $15 billion (cost of countermeasures).

Figure 5   Tornado Diagram Showing the Sensitivity of Input Parameters to the Difference Between the Expected Equivalent Costs of No Countermeasures and Countermeasures

Note. The vertical line is located at the difference of the base case expected equivalent costs of about $4 billion; the black bar segments indicate the parameter values where no countermeasures are preferred and the grey bar segments indicate the parameter values where countermeasures are preferred.

left area (no countermeasures) and the upper right area (countermeasures) is defined by the combination of the probability of an attempt and the economic losses at which the two decisions have identical equivalent expected costs. For example, if the probability of an attack is 0.35 in the next ten years and the economic losses are $100 billion, then the two expected costs are about equal. Combinations of probabilities and economic losses in the lower left suggest not deploying countermeasures, and combinations in the upper right area suggest employing countermeasures.

Figure 10 shows the same relationship, but for a higher cost of countermeasures ($30 billion). As expected, the area for which countermeasures are pre-

ferred (upper right) is now much smaller. In other words, to justify expensive DIRCM countermeasures, much higher probabilities of an attempt and much higher economic losses are required.

So far the analysis has focused on the equivalent expected costs of deciding on whether or not to choose MANPADS countermeasures. One might argue that it is not the expected costs that should matter in this case, but the possibility of catastrophic consequences and how MANPADS countermeasures can reduce this probability. To explore this issue, we plotted the probabilities at all end nodes of the decision tree in Figure 1.[8] The results are shown in Figure 11.

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[8] We thank Bob Clemen for this suggestion.

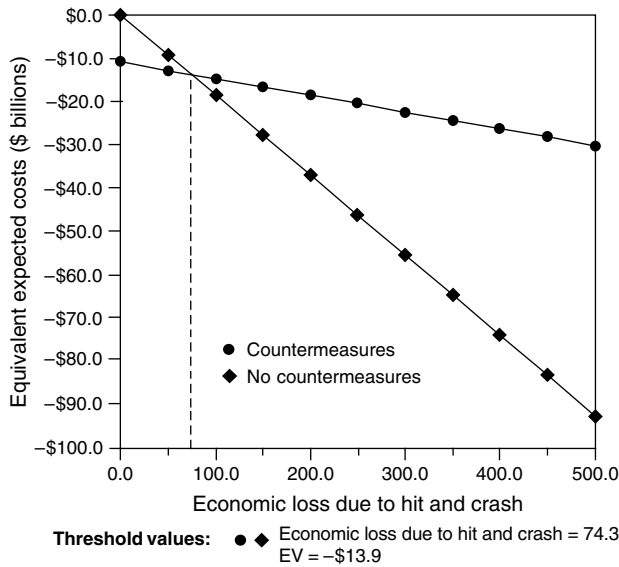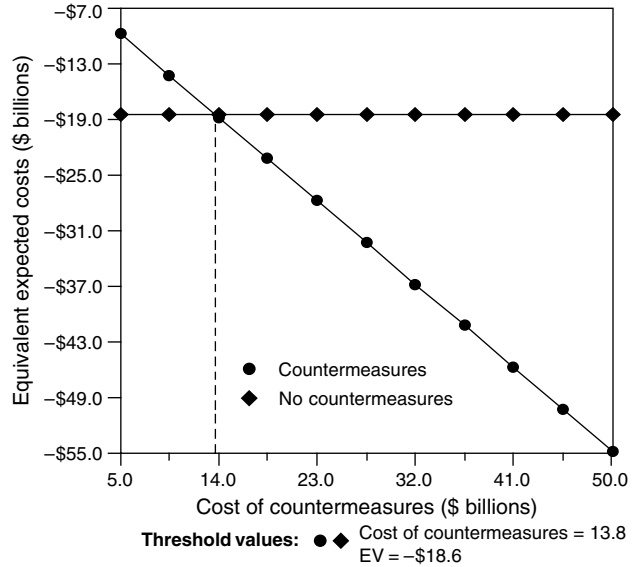**Figure 6   Sensitivity Analysis on the Economic Loss Due to a Hit and Crash**

Threshold values: ● ◆ Economic loss due to hit and crash = 74.3
EV = −$13.9

Figure 8   Sensitivity Analysis on the Cost of MANPADS Countermeasures

Threshold values: ● ◆ Cost of countermeasures = 13.8
EV = −$18.6

Looking at the right tail (high expected equivalent costs) of this probability distribution, we see that the probability of a catastrophic consequence is reduced from 0.10 to 0.01 or by a factor of 10 by using countermeasures. This base case result assumes that the effectiveness of deterrence is 50% and the effectiveness of deflecting the missile is 80%. If either or both of these effectiveness factors increase, the probability

of the high end consequence with countermeasures decreases correspondingly.

4.   Conclusion

In this study we have applied a decision tree analysis, combined with several sensitivity analyses, to inform the ongoing public debate about the cost-effectiveness of proposed directed infrared countermeasures to

Figure 7   Sensitivity Analysis on the Probability of an Attempt

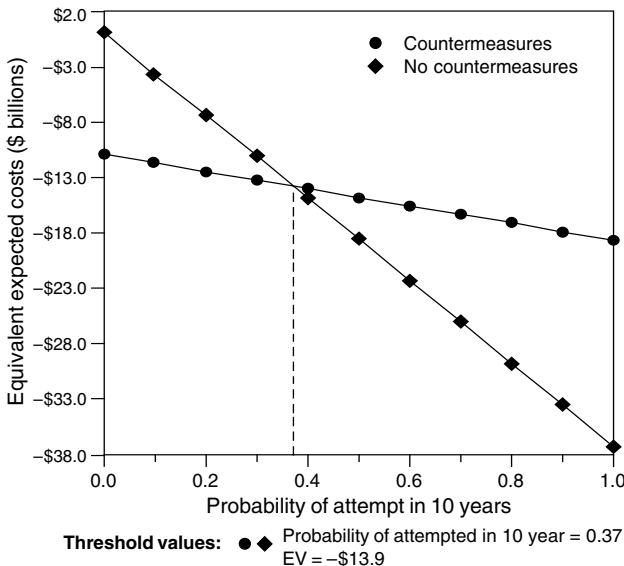Threshold values: ● ◆ Probability of attempted in 10 year = 0.37
EV = −$13.9

Figure 9   Two-Way Sensitivity Analysis on the Probability of an Attempt and the Economic Loss Due to a Hit and Crash (Cost of Countermeasures = $10 Billion)
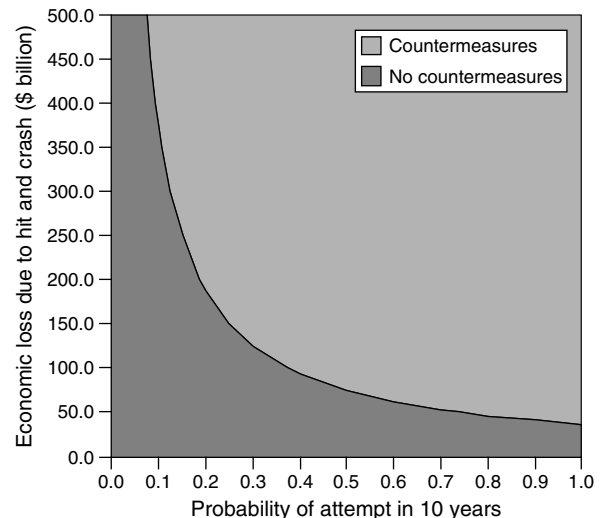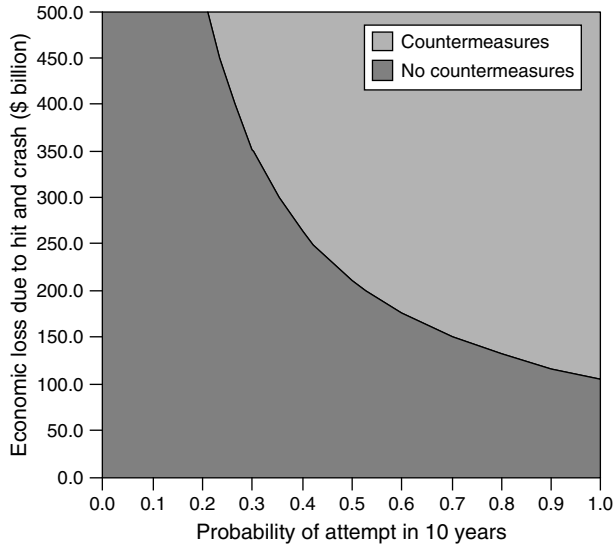
Figure 10 Two-Way Sensitivity Analysis on the Probability of an Attempt and the Economic Loss Due to a Hit and Crash (Cost of Countermeasures = $30 Billion)

protect commercial airliners from MANPADS attacks by terrorists. The analysis indicates that of the 17 variables that affect the decision of whether or not to deploy these countermeasures, 3 are especially important:

1. The economic losses due to a MANPADS attack
2. The probability of a MANPADS attempted attack
3. The cost of countermeasures

While this may not be surprising, it is surprising that many of the other variables are less important, at least in a range that many experts consider plausible. As a result, all things being equal, we believe that countermeasures can be cost-effective if the probability of such an attack is large (>0.40 in ten years), the economic losses are very large (>$75 billion), and the cost of countermeasures is moderate (<$15 billion).

In addition, the analysis suggests that the probabilities of catastrophic consequences are significantly reduced (by at least a factor of 10) with MANPADS countermeasures. If MANPADS countermeasures were completely effective or if they deterred terrorists completely from launching a MANPADS attack, the catastrophic consequences would be eliminated, though consequences due to attempts and misses might still be severe.

The two main contested variables are the cost of a MANPADS attack to the economy and the cost of countermeasures. Several recent studies indicate that the cost of an attack to the economy can be quite large. If the economic impacts approach those of 9/11 they can be in the hundreds of billions of dollars. It is unlikely that a single MANPADS attack would

Figure 11 Probabilities of Consequences Associated With MANPADS Attacks (Black Solid Bar: with Countermeasures; Grey Shaded Bar: Without Countermeasures)
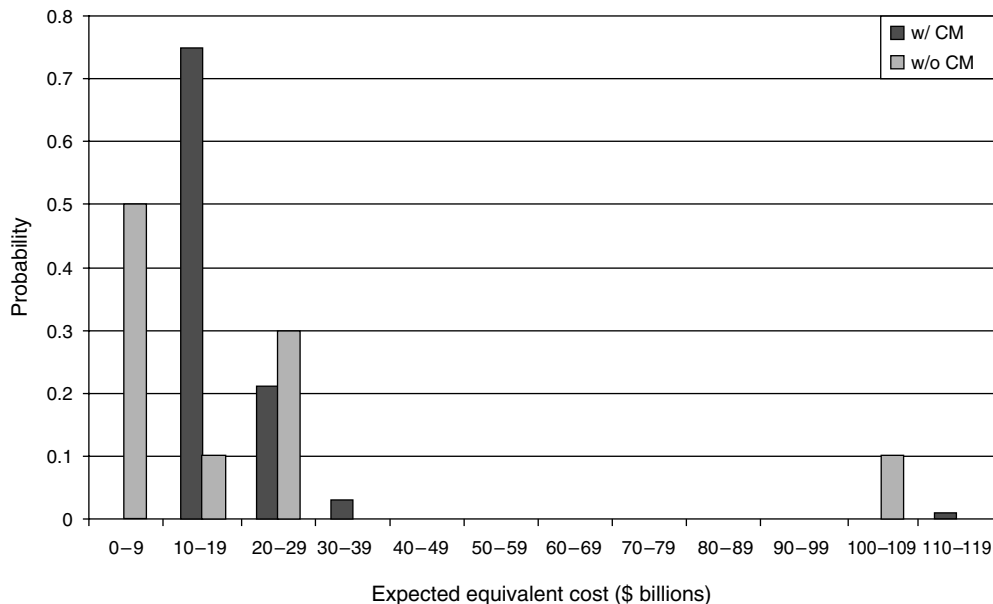
produce such impacts. Multiple and repeated attacks that show the intent and the capability of terrorists to destroy commercial airplanes could have a substantial economic effect, but multiple and repeated attacks also have a lower probability of occurring.

This model focused on DIRCM countermeasures against heat seeking missiles, but the model can be adapted to evaluate the cost-effectiveness of other countermeasures for other surface-to-air attacks, using, for example, laser-guided missiles, rocket-propelled grenades, mortars, or large caliber rifles. Each weapon will have its own parameters (e.g., hit and crash probabilities) and consequences.

The model also can be used to investigate alternative countermeasures, for example hardening the airplanes or pilot training (reducing the probability of a crash, given a hit), perimeter control (increasing the probability of interdiction), or improved methods for detecting MANPADS at our borders (reducing the probability of an attempt). In addition, the analysis focused on one attack, but it can be adapted to multiple simultaneous or sequential attacks. This involves assessing probabilities over the number of attempted attacks, the number of successes and the consequences of multiple attacks.

Additional research that reduces the uncertainty of each of the three key parameters (probability of an attack, economic loss, and cost of countermeasures) might be useful. Regarding the probability of an attack, it is unlikely that additional research will provide better estimates. Intelligence on this issue is likely to remain vague and ambiguous. One potentially useful study is to determine how difficult or easy it is to smuggle MANPADS into the United States.

Regarding economic impacts, the existing studies provide a large range—somewhere between $40 billion (Santos and Haimes 2004) and $400 billion (high end of the study by Gordon et al. 2006). Our analysis suggests that the tipping point may be around $75 billion, using a 50% probability of an attack in ten years. Thus, some additional research on economic impacts may be quite useful.

Additional research on the capital and operational cost of the countermeasures would also be useful. Capital cost estimates vary by a factor of three (from $1 million per plane to $3 million per plane), and

operational costs vary even more, because of the uncertainties surrounding maintenance and repair schedules and other costs due to maintaining security and protecting the equipment. It would therefore be very useful to obtain firmer cost estimates prior to making a final decision on deploying MANPADS countermeasures.

By far the most important research to be done is on the effects of countermeasures on terrorist motivations and intent to attack commercial airplanes in the United States. One would assume that the installation of countermeasures would significantly reduce the probability of an attack using infrared guided MANPADS, but it is also reasonable to assume that the probability of attacks using non-IR-guided MANPADS, RPGs, high-caliber rifles, mortars or other current or future weapons would increase. Furthermore, the likelihood of attacks on foreign airlines that may not have installed countermeasures would increase. Research on these dynamic effects, using sequential decision trees with changing probabilities of terrorist attack modes may shed light on this issue.

When this article was written, the decision of whether or not to install DIRCM countermeasures on commercial airplanes was still pending. However, it is clear that the analysis had an impact on the decision-making process. The office in the Department of Homeland Security concerned with MANPADS was initially skeptical of this analysis. After the CREATE team provided SPO staff with briefings and the analysis and tools described in this article, this office issued a statement in April, 2006:

> CREATE has provided several very timely, relevant deliverables to the Counter-MANPADS Systems Program Office.... As the program has progressed, there has been a growing need to show the benefits relative to the costs of outfitting the commercial aircraft fleet with such technologies.... The CREATE products, which include an economic analysis of the indirect costs associated with a successful MANPADS attack, have helped fill this void. (Counter-MANPADS Program office, e-mail message to von Winterfeldt.)

Furthermore, the analysis has shown that neither of the two extreme arguments by anti and pro MANPADS countermeasures proponents is quite right. According to this analysis, the decision is on the tipping point and it would be very useful to conduct

additional studies, especially on the costs of MAN-PADS countermeasures and on the economic impacts of MANPADS attack. Additional value of information and value of control analyses would be useful. Some of this can be done within the existing framework.

This analysis also offers some lessons for risk and decision analysts interested in applying analysis tools to terrorism. First is a message of hope. The main criticism of using standard risk and decision analysis to terrorism has been that we cannot assess the probability of an attack. This analysis shows that one can come to reasonable conclusions with a wide range of probabilities of an attack. The other criticism leveled at risk and decision analysis is that terrorists will shift their tactics, once a particular decision (e.g., MANPADS countermeasures) has been implemented. While this is true, standard methods exist to expand the decision tree to analyze the effects of these shifting probabilities of attack. An extension of this analysis is currently underway at the Center for Risk and Economic Analysis of Terrorism Events.

Acknowledgments

References

Bennett, R. K. 2003. Think the unthinkable. *Tech Central Station* (August 14). http://www.techcentralstation.com/081403D.html.

Bolkcom, C., B. Elias. 2006. Homeland security: Protecting airliners from terrorist missiles. Foreign Affairs, Defense, and Trade Division, Congressional Research Service (CRS) (Updated February 16, 2006).

Chow, J., J. Chiesa, P. Dreyer, P. Eisman, T. W. Karasik, J. Kvitky, S. Lingel, D. Ochmanek, C. Shirley. 2005. Protecting commercial aviation against the shoulder-fired missile threat. RAND Occasional Paper. RAND Corporation, Santa Monica, CA.

Decision Support Services. 2005. Decision tree add-in. San Francisco, http://www.treeplan.com.

GAO (Government Accountability Office). 2004a. The Department of Homeland Security needs to fully adopt a knowledge-based approach to its Counter-MANPADS Development Program. U.S. General Accountability Office, GAO-04-341R, Washington, D.C.

GAO (Government Accountability Office). 2004b. Further improvements needed in U.S. efforts to counter threats from Man-Portable Air Defense Systems. U.S. General Accounting Office, GAO-04-519, Washington, D.C.

GAO (Government Accountability Office). 2005. State Department needs to resolve data reliability problems that led to inaccurate reporting to Congress on foreign arms sales. GAO-05-156R, Washington, D.C. (January 28).

Gordon, P., S. Kim, J. E. Moore II, J. Park, H. W. Richardson. 2006. The economic impacts of a terrorist attack on the U.S. commercial aviation system. Submitted to *Risk Anal.*

Grau, L. R. 1998. The RPG-7 on the battlefields of today and tomorrow. *Infantry* (May–August). http://www.globalsecurity.org/military/library/report/1998/infantry-rpg.htm.

Hunter, T. B. 2002. The proliferation of MANPADS. *Jane's Intelligence Rev.* (November 28). http://www.janes.com.

Jane's Intelligence Review. 2003. Mombasa attack highlights increasing MANPADS threat. **15** (February) 26–31.

O'Sullivan, T. M. External terrorist threats to civilian airliners: A summary risk analysis of MANPADS, other ballistic weapons risks, future threats, and possible countermeasures policies. Working paper, Center for Risk and Economic Analysis of Terrorism Events (CREATE), University of Southern California (November 2004; revised February 2005).

Phelps, M. 2003. Do SAMs pose a real threat to civil aviation? *Aviation Internat. News* (January). http://www.globalsecurity.org/org/news/2003/0301-sam-threat01.htm.

Raiffa, H. 1968. *Decision Analysis*. Addison-Wesley, Boston.

Santos, J. R., Y. Y. Haimes. 2004. Modeling the demand reduction input-output (I-O) inoperability due to terrorism of interconnected infrastructures. *Risk Anal.* **24** 1437–1451.

Shanker, T. 2002. Ideal terror weapons: Portable deadly, plentiful missiles. *New York Times* (November 29). http://www.nytimes.com.

Space Daily. 2003. DHL aircraft hit by missile over Baghdad had lost all hydraulics (December 8). http://www.spacedaily.com/news/iraq-03a.html.

Treeage Software, Inc. 2005. *Treeage Pro 2005*. http://www.treeage.com.

Violence Policy Center. 2002. Sitting ducks: The threat to chemical and refinery industry from 50 caliber sniper rifles. http://www.vpc.org/50caliber.htm.

Violence Policy Center. 2005. Clear and present danger: National security experts warn about the danger of unrestricted sales of 50 caliber anti-armor sniper rifles to civilians. (July). http://www.vpc.org/50caliber.htm.

von Winterfeldt, D., W. Edwards. 1986. *Decision Analysis and Behavioral Research*. Cambridge University Press, Cambridge, UK.