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Optimal Allocation of Resources in Airport Security: Profiling vs. Screening

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Abstract

This model examines the role of intelligence gathering and screening in providing airport security. We analyze this problem using a game between the government and a terrorist. By investing in intelligence gathering, the government can improve the precision of its information. In contrast, screening can be used to search a passenger and thereby deter terrorist attacks. We determine the optimal allocation of resources between these two strategies wherein we model the role of intelligence using the concept of supermodular precision. One striking result is that under certain circumstances, an increase in the investment in intelligence can induce a more devious terrorist to attack with a higher probability. We also find that when there is a cost-reducing innovation in the screening technology, then the optimal investment in intelligence gathering can go either way. However, such an innovation unambiguously improves social welfare. Another interesting implication is that a developed economy would value intelligence inputs more than a developing economy. We also examine the efficacy of a program such as PreCheck that allows some select passengers expedited screening in exchange for voluntarily revealing information about themselves. Our analysis shows that such a program can be used to cushion the adverse effect of budgetary shortages. Finally, we also examine the role of enhanced punishment on the optimal level of intelligence. We find that the result can go both ways. If the initial level of punishment is high, then any further enhancement reduces the optimal level of intelligence gathering. However, this result is reversed if the initial level of punishment is low.

Key words: Agencies, Cost effectiveness, Tactics/strategy.

History: This paper was first submitted on December 10, 2012 and has been with the authors for 10 months for 2 revisions.

1 Introduction

In recent times, there have been several high-profile instances of terrorism. According to the Global Terrorism Database, there have been over 5000 terrorist attacks all over the world in 2011, resulting in over 7,000 deaths (GTD, 2013). The main difficulty in deterring terrorist acts (as opposed to conventional war) is that terrorists have a much higher advantage of surprise, that is, they can attack at a time and place of their choosing using possibly a novel method of attack. This implies that the cost of defending against terrorist attacks is likely to be very high (Sandler, Arce and Enders 2008). Airlines have traditionally been one of the major targets of terrorists. Hence, naturally there has been increased attention towards aviation security and numerous measures have been implemented to make air travel safer. This is reflected in the Transportation Security Administration (TSA) budget for aviation which now exceeds \$6 billion dollars per year (Department of Homeland Security 2011). According to Mueller and Stewart (2011, p. 185), expenditure on preventing a mass transit attack has a benefit to cost ratio of only 0.015 meaning that the benefit is only around 1.5 cents for every dollar spent in security. Therefore, it is imperative to determine more efficient ways of providing security. Of course, one might also want to know if it is efficient for the government to provide aviation security. Research by Heal and Kunreuther (2005) shows that the government does indeed have a meaningful role to play in the provision of aviation security.

In this study, we focus on two important (but related) research questions in the aviation security domain. The first one is to determine the socially optimal level of security. The second one is to determine the optimal allocation of resources between profiling and screening, given a chosen level of security. We use a two period game between a government and a representative individual. The government as a whole has two objectives. On the one hand, it would like to secure the airports, while on the other hand, it would like to minimize the social cost of security. The individual enjoys utility from carrying out a successful attack that is privately known only to him. In consonance with the literature on crime, we call this the "private benefit" of the individual.

In the first period, the government invests in profiling. The purpose of profiling is to estimate the private benefit of the individual, because in equilibrium, an individual with a higher private benefit is more likely to attack. A higher investment in intelligence gathering enables the government to be more accurate in its estimation about a passenger's type. We model the role of intelligence

gathering using the concept of supermodular precision (Ganuza and Penalva 2010). In the second period, the individual and the government simultaneously select a move. The individual decides whether to attack or not, while the government decides whether to screen or not. At the end of this period, both government and individual earn their payoffs depending upon the pair of actions chosen. Below, we summarize some of our key questions and findings.

In equilibrium, how does an increase in intelligence gathering change the behavior of a potential terrorist as well as of airport security? We find that everything else remaining constant, an increase in the expenditure on intelligence may increase the probability of attack of a highly motivated terrorist (that is, someone with a higher utility from an attack), while reducing the probability of an attack of a less motivated terrorist. This implies that after an increase in the expenditure on intelligence attacks, successful attacks (that is, those that escape detection) are more likely to be committed by highly motivated terrorists. To the extent that the amount of damage is positively related with the motivation of terrorists, it means that after an increase in the expenditure on intelligence gathering, successful attacks will have a higher impact on average (although their likelihood may reduce). We also find after an increase in the expenditure on intelligence gathering, airport security decreases the rate of screening. The reason is that superior intelligence allows the government to better estimate a passenger's type and this allows it to focus its screening resources on passengers who are more likely to be a threat.

What is the role of intelligence in providing security? If the provision of security is the only concern, then intelligence gathering does not have a major role to play. After all, the government can screen every passenger and provide almost perfect security if it chooses to. However, there are at least two problems with this approach once we account for the cost of providing security. The first one is that resources spent in providing security has other competing uses (that is, it has an opportunity cost) and excessive expenditure on security may therefore reduce social welfare. The other one is that excessive screening means that huge lines will form in the airport. Therefore part of the social cost of security is due to the value of passengers' time lost in the security lines in the airport. Quite naturally, when the cost of security is not a concern, the optimal expenditure in intelligence gathering should be 0. However, better intelligence allows the government to direct screeners towards passengers who are more likely to be a threat. If the rate of screening goes down, then this saves money. Further, the security lines in the airport will be shorter leading to a lessening

of the congestion externalities. Thus, when we account for the opportunity cost of resources as well as of time, then the optimal expenditure on intelligence gathering is positive.

In this paper, we also determine the impact of changes to some parameters. For example, we consider the impact of an innovation that reduces the cost of screening per passenger. One would expect that such a decrease would reduce the optimal expenditure on intelligence gathering since screening is no longer so costly. Rather surprisingly, we find that a reduction in the cost of screening leads to a decrease in the expenditure on intelligence only when the opportunity cost of resources is sufficiently high. However, such an innovation unambiguously increases social welfare. This result, as well as other comparative statics, have been discussed in detail in Section 7.

2 Literature Review

The related literature has focused on two main aspects- profiling and screening, and the relationship between them. The concept of statistical profiling was originally developed by Coate and Loury (1993) to explain the concept of rational discrimination. The idea of profiling can be modeled using this literature. The TSA can only observe a signal about a person based on observable characteristics and can classify a person as a potential suspect on the basis of the observed signal. Yetman (2004) using a similar framework argues that discriminatory screening may Pareto-dominate non-discriminatory screening that ignores observable signals about the true nature of the passengers. Persico and Todd (2005) extend a model of crime detection into the context of airport security. They show that if a group with a higher propensity to commit terror is screened more frequently, then there will be a reduction in terrorist acts from this group (assuming that the profiling system is reasonably accurate), but this may be more than compensated by an increase in terrorist acts from the other group.

Basuchoudhary and Razzolini (2006) show that selective screening of passengers based on signals about their true nature may not always be the optimal strategy. Babu et al. (2006) conclude that it is optimal to classify passengers into different groups even when all individuals are observationally equivalent. This result therefore seems to endorse the idea of using different levels of inspection for different individuals which is the purpose of profiling. Nie et al. (2009) in an extension of this study demonstrate that such a passenger grouping strategy would result in a more efficient security

system when the assumption that they are indistinguishable in terms of risk is relaxed further supporting the use of profiling. McLay et al. (2010) analyze how to assign individuals to different screening levels based upon their profiles (such as the one generated by CAPPS). The effectiveness of profiling has also been studied and debated in several other papers such as Press (2009 and 2010), Meng (2011), and Reddick (2011). Jackson, Chan and LaTourrette (2012) evaluates the benefits of a policy similar to profiling but one focusing on identifying the low risk population, i.e., the frequent travelers. They point out that the screening rate of these select group of travelers can be reduced. The resources freed up can then be used to screen the remaining population about whom less information is available. Nie et al. (2012) develop a simulation based queueing model to determine the assignment of passengers (who could be different in terms of the risk they pose) to the selectee lane with an objective of maximizing the passenger checkpoint system's security effectiveness. Specifically, they focus on the system's probability of true alarm.

There is also a literature on screening, which primarily focuses on the impact of an improvement in the screening technology. Persico and Todd (2005) examine this question and find that an improvement in the screening technology unambiguously leads to a fall in the number of terrorist attacks. There is a second aspect of the screening literature such as Nikolaev, Jacobson and McLay (2007) that analyzes the interaction between the installation of screening devices and their optimal usage. Then there is also a third dimension in the screening literature that examines methods of optimally screening baggage (see for example, Jacobson et al., 2005 and 2006). In a related context, Nie (2011) and Jacobson et al. (2006) study the configuration of devices that would be optimal for minimizing the total cost of screening. Bier and Haphuriwat (2011) analyze the problem of optimal screening in the context of port security. As pointed out earlier, there has also been research (such as Wang and Zhuang (2011)) on the impact of screening policies on congestion.

Finally, there is a third major branch of the literature that examines the relationship between profiling and screening policies. Cavusoglu, Koh and Raghunathan (2010) is a contribution along this dimension. This paper examines if profiling and screening work together or against each other in providing security. In order to answer this question, the authors first look at a model of security that is similar to the one used by TSA and conclude that profiling is beneficial when the quality of the screening technology is relatively low. Further, this result can be overturned when the quality of the screening technology is high. Our project is designed to examine these issues in further detail

and in doing so bridge several gaps in the literature.

We discuss the basic model designed to achieve these objectives in the next section.

3 Model

We analyze a game between a government and a representative individual; this individual will be referred to as individual i . Suppose individual i has a benefit b_i from a successful attack; $b_i \in [0, \bar{b}]$. This benefit is privately known only to individual i and will be referred to as the "private benefit" of i . To everyone else, b_i is a random variable that is distributed on the interval $[0, \bar{b}]$ and follows the probability density function $f^B(\cdot)$ with $F^B(\cdot)$ being the corresponding distribution function. The private benefits are assumed to be identically and independently distributed. It is also possible that individual i chooses to attack, but the attack fails. In such a scenario, individual i is awarded a punishment z . The notations used in this paper are summarized in Table 1.

One of the processes involved in airport security is screening passengers. Throughout this paper, we use the term "screening" as a synonym of "searching" or "inspecting." Screening of individuals requires some time. Since there is an opportunity cost of time, therefore screening of passengers imposes a cost on the representative passenger. The opportunity cost of time wasted for screening is the benefit that the individual could have enjoyed by using the time elsewhere. Thus, the opportunity cost of time depends on wage rates as well on the value of leisure. Additionally, the amount of time spent in the security checkpoint depends on the *ex ante* probability of screening (because in a large population with identical passengers, the proportion of passengers that are screened is given by the probability of screening). The value of time wasted at a security checkpoint is commonly known as a congestion externality and is denoted by T .

Next, we consider the utility of a representative individual, called individual i . Individual i has two possible actions, which we label as "Attack" and "Do not Attack" and i 's gross utility is given by

$$\begin{aligned}
 & b_i - T && \text{if Attack is Successful,} \\
 & -z - T && \text{if Attack Fails,} \\
 & -T && \text{if Do not Attack.}
 \end{aligned} \tag{1}$$

A person can avoid incurring the congestion externality if he chooses to use some other mode of

transportation. However, conditional on choosing to fly, there is no way of avoiding this cost. Thus, the congestion externality does not play any role in the decision to attack. However, we show later, that the congestion externality matters in determining the socially optimal level of investment in profiling.

Next, suppose that the government spends an amount $k > 0$ in intelligence gathering and privately observes an imperfect intelligence report $\theta_i \in [0, \bar{b}]$ about b_i . The report θ_i is a measure of individual i 's propensity to attack. Thus, consider b_i as i 's actual propensity to attack and θ_i as i 's assessed propensity to attack from the perspective of the government. As a result, b_i and θ_i are stochastically related to each other. The government can improve the quality of its information by investing more money in intelligence. Later on, we define the nature of the relationship between these two random variables, and the meaning of an improvement in the intelligence assessment.

Conditional on having observed an intelligence report θ_i , the government has to choose between two possible actions - "Screen" or "Do not Screen." We assume that screening can prevent an attack with certainty. It is possible to extend the model to incorporate cases in which such screening can deter an attack with a probability less than 1, but such an extension does not add anything interesting to our analysis. Let z be the punishment of i if he is caught and convicted of planning an attack. There is a case for designing the optimal punishment of a convicted terrorist; however, since this is not the purpose of this study, therefore, we treat z as an exogenous variable.

Summarizing the description above, we can write the expected payoff of individual i as follows:

$$\begin{aligned} P(\text{Not Screen}) b_i - P(\text{Screen}) z - T & \text{ if } \text{Attack,} \\ -T & \text{ if } \text{Do not Attack.} \end{aligned} \tag{2}$$

Notice that i incurs the congestion externality regardless of his action. Next, consider i 's payoff if he chooses to attack. In that case, i 's payoff is b_i if he is not screened, and therefore not caught. On the other hand, if i is screened, then he will be detected with certainty, in which case, he only suffers the punishment z . Consequently, i 's expected payoff if he chooses to attack is as given above.

We now focus on the government's payoff. The government can choose whether or not to screen a passenger. If the government wants to screen i , then it has to incur a cost of c . Thus, c is the constant marginal cost of screening. We assume that $c > 0$ following extant literature (some

examples include: Jacobson et al. (2006) and Cavosgulu, Koh and Ragunathan (2010)). Next, let $L(b_i)$ denote the damage if i attacks successfully. Naturally, there has to be a relationship between the private benefit of i and magnitude of the damage if i attacks. We assume that a higher value of b_i should be associated with a higher value of $L(b_i)$ as well. In other words, we assume that

$$L'(b_i) > 0. \quad (3)$$

The job of the government is to minimize the loss from such attacks, to the extent possible. Most democratic governments tend to be risk-averse about terrorist attacks because these attacks attract a lot of attention in the media and thereby show the political leadership in a poor light. Let the Bernoulli utility function of the government be denoted by $u(\cdot)$ (Mas-Colell, Whinston and Green 1995, p. 184); $u'(\cdot) > 0$, $u''(\cdot) < 0$. The expected payoff of the government is given by

$$\begin{aligned} & u(-c - k) && \text{if Screen,} \\ P(\text{Attack}|\theta_i) u(-L(b_i) - k) + P(\text{No Attack}|\theta_i) u(-k) && \text{if Do not Screen.} \end{aligned} \quad (4)$$

In order to understand the payoff of the government, we first consider the case when it screens individual i . In such a case, there is no damage, regardless of i 's intentions. However, there is a cost of providing security. The first kind of cost is the cost of generating an intelligence report about i and this is measured by k . The second kind of cost is the cost of screening him, and this is measured by c . Hence, the net payoff of the government if it decides to screen i is given by $u(-c - k)$. Next, consider the case in which the government chooses not to screen an individual. Observe that in this case, the government does not incur the screening cost c . Also, notice that the outcome is stochastic from the perspective of the government, since the outcome depends on the action chosen by i . Therefore, if i chooses to attack and the government does not screen him, then i successfully carries out an attack and inflicts a loss of $L(b_i)$. Consequently, in this case, the payoff of the government is $u(-L(b_i) - k)$. On the other hand, if i does not attack, then there is no loss even if he is not screened. Consequently, the government's payoff in this case is $u(-k)$. Combining these terms, we derive the expression for the expected payoff of the government.

In our model, we assume that $L(0) > c$, that is the loss inflicted by the most benign kind of attacker is more than the cost of screening him. As a justification, notice that the damage from

even the most benign kind of terrorist attack is much more than the cost of screening an individual. This assumption along with (3) implies that $L(b_i) > c$ for all b_i .

At this stage, we would like to clarify the difference between "profiling" and "screening" in the model. The term profiling refers to the act of gathering intelligence and subsequently classifying different individuals into different risk classes. In terms of our model, profiling refers to the act of generating θ_i . We show that in the equilibrium of this game, every type of individual has a positive probability of attacking, although a person with a higher value of θ is more likely to attack. Thus it is possible, that one passenger with a high value of θ chooses not to attack, while another passenger with a low value of θ chooses to attack. The only way to deter such attacks is by screening passengers in the airport.

The timeline of the game is as follows: In Period 1, the government invests k in gathering intelligence. At the end of this period, the government privately observes the intelligence report. In period 2, individual i and the government simultaneously select a move. Individual i decides whether or not to attack, while the government decides whether or not to screen i . At the end of this period, both players earn their payoffs depending upon the pair of actions chosen.

4 Role of Intelligence Input

Below, we discuss the nature of the relationship between the intelligence report θ and the private benefit b and how it is affected by the expenditure on intelligence gathering, denoted by k . Let $F^{B\Theta}(b, \theta; k)$ be the joint distribution function of b and θ for a given level of investment expenditure k , with the marginal distribution functions being $F^B(b; k)$ and $F^\Theta(\theta; k)$. The signal θ is assumed to be affiliated with the private benefit b . Therefore, the following inequality holds for all $b''_i \geq b'_i$ and $\theta''_i \geq \theta'_i$ (see, for example, Krishna 2010, p. 286):

$$f^{B\Theta}(b''_i, \theta''_i; k) f^{B\Theta}(b'_i, \theta'_i; k) \geq f^{B\Theta}(b''_i, \theta'_i; k) f^{B\Theta}(b'_i, \theta''_i; k).$$

Let x and y be defined as follows: $x = F^B(b; k)$ and $y = F^\Theta(\theta; k)$.

Notice that x and y are obtained by the probability integral transformation of b and θ respectively. Further, x and y are themselves random variables that can be shown to follow the Uniform

Notations	Definitions
b_i	benefit to individual i from a successful attack
θ_i	intelligence report about individual i
k	amount spent on gathering intelligence about i
$F^{B\Theta}(b, \theta; k)$	joint distribution function of b and θ given k
$F^B(b; k)$	marginal distribution function of b given k
$F^\Theta(\theta; k)$	marginal distribution function of θ given k
$f^B(b; k)$	density function of b given k
x	a monotonic transformation of b ; x is equal to F^B
y	a monotonic transformation of θ ; y is equal to F^Θ
$F^{XY}(x, y; k)$	joint distribution of x and y given k (also known as the copula)
$f^{XY}(x, y; k)$	joint density function of x and y given k
c	cost of screening i
z	punishment awarded to i if caught
$L(\cdot)$	damage from a successful attack
$u(\cdot)$	Bernoulli utility function of the government
$\hat{\alpha}(y_i)$	government's estimate of the probability that i will attack
$\alpha(x_i)$	actual probability of attack of i
$\hat{\beta}(x_i)$	i 's estimate that he will be screened, given that i 's actual private benefit is x_i
$\beta(y_i)$	actual probability that the government will screen i
p	probability of detecting an individual upon screening
T	congestion externality
$q(k)$	<i>ex ante</i> probability of screening i
λ	opportunity cost of one unit of resource used in providing security
M	total opportunity cost of all resources spent in providing security
τ	opportunity cost of time per unit required to screen i
G	equilibrium payoff of the government in the screening stage
W	social welfare

Table 1: List of Notations

distribution in $[0, 1]$. For the rest of the paper, we use x_i instead of b_i to measure the private benefit of i . This is a valid transformation of b_i since there is a one-to-one correspondence between b_i and x_i . Similarly, we use y_i instead of θ_i to measure the signal that the government has regarding individual i . There are several reasons why we present the results below in terms of (x, y) instead of (b, θ) . First, the analysis is quite general since it does not depend on the properties of a specific distribution. Second, since x and y follow the Uniform distribution, therefore several results (such as (19) below) can be derived quite neatly without having to invoke additional assumptions. Third, this formulation is easily amenable to any algebraic treatment and hence the comparative static results can be derived easily without any loss of generality.

The joint distribution of (x, y) is known as a copula, and we denote this by $F^{XY}(x, y; k)$. It follows from Sklar's Theorem (Nelsen 2006, p. 21) that there exists a copula $F^{XY}(\cdot)$ such that for all (b, θ) , $F^{B\Theta}(b, \theta; k) = F^{XY}(x, y; k)$. Let $f^{XY}(x, y; k)$ be the joint density function of x and y . It is related to the copula function as follows:

$$f^{XY}(x, y; k) = \frac{\partial^2 F^{XY}(x, y; k)}{\partial x \partial y}.$$

We denote the marginal distributions of x and y by $F^X(x; k)$ and $F^Y(y; k)$ respectively. Since x and y follow the uniform distribution, therefore, $F^X(x; k) = x$ and $F^Y(y; k) = y$. The conditional distribution functions are denoted by $F^X(x|y; k)$ and $F^Y(y|x; k)$. Using the above properties, the conditional distributions can be derived from the joint distributions as follows:

$$F^X(x|y; k) = F_y^{XY}(x, y; k) \text{ and } F^Y(y|x; k) = F_x^{XY}(x, y; k) \quad (5)$$

where $F_l^{XY}(x, y; k)$ is the partial derivative of $F^{XY}(x, y; k)$ with respect to l ; $l = x, y$. Finally, we denote the conditional density functions by $f^X(x|y; k)$ and $f^Y(y|x; k)$.

Since x and y are affiliated, therefore the following relationship also holds (Nelsen 2006, pp. 196-201):

$$F_{xx}^{XY}(x, y; k) < 0 \text{ and } F_{yy}^{XY}(x, y; k) < 0. \quad (6)$$

4.1 Supermodular Precision Using Copulas

In the model, the government observes the intelligence report y_i about the private benefit x_i but not the private benefit itself. Thus, from the government's perspective, the report y_i is simply a "signal" about x_i . On the other hand, an individual only observes x_i but not y_i . Thus, from the perspective of individual i , the true type is a signal about the intelligence report that the government will have about i . Individual i knows that the government will decide whether or not to screen him based upon y_i . Individual i does not observe the exact value of y_i , but can determine its conditional distribution since he can observe x_i . Thus, i chooses an action based upon his estimate of the value of y_i .

The role of the investment in intelligence k is to improve the precision of the information. When there is an increase in k , then the degree of association increases between x_i and y_i . The concept of precision depends upon the dispersion of a random variable and has been discussed in Ganuza and Penalva (2006 and 2010). Notice that from the government's perspective, y_i is a signal of x_i . It follows from Ganuza and Penalva (2010, p. 1010) that an increase in k improves the precision of y_i as a signal of x_i if it increases the dispersion of $E[x_i|y_i, k]$. The intuition is that an increase in the quality of the information should make x_i more sensitive to y_i which would result in higher dispersion of $E[x_i|y_i, k]$. There are multiple ways to measure dispersion of a random variable. One such definition is due to Bickel and Lehmann (1976) and is reproduced from Ganuza and Penalva ((2006, p. 10) and (2010, p. 1010)).

A random variable s'' is said to be greater in the dispersive order (or more Bickel-Lehmann disperse) than another random variable s' if for all $\alpha_1, \alpha_2 \in [0, 1]$; $\alpha_2 > \alpha_1$, the following inequality holds:

$$F_{s''}^{-1}(\alpha_2) - F_{s''}^{-1}(\alpha_1) \geq F_{s'}^{-1}(\alpha_2) - F_{s'}^{-1}(\alpha_1)$$

For an illustration, consider Figure 1. Notice that the distribution function of s'' , denoted by $F_{s''}(\cdot)$, intersects $F_{s'}(\cdot)$ (the distribution function of s') from above. Thus, in order to gain an additional cumulative probability of $(\alpha_2 - \alpha_1)$, the random variable s'' has to increase by more. Thus, s'' is more disperse than s' .

We now use the concept of Bickel-Lehmann dispersion to define the notion of supermodular precision below. In order to do so, we need to introduce some further notations. Let $V(y, k)$ denote

$E[x|Y = y; k]$. Notice that $V(y, k)$ itself is a random variable. Below, we let the distribution of $V(y, k'')$ to be more Bickel-Lehmann disperse than the distribution of $V(y, k')$ for $k'' > k'$.

An increase in the quality of information from k' to k'' improves the precision of the signal in the supermodular sense iff, for all $y' < y''$ and $k' < k''$, the following inequality holds (Ganuza and Penalva (2010), p. 1012):

$$V(y'', k'') - V(y', k'') \geq V(y'', k') - V(y', k').$$

In order to understand the above condition, let us consider Figure 2. In the diagram, there are two lines that depict the function $V(\cdot, k)$ and the flatter line corresponds to a lower value of k . Now suppose the value of the signal increases from y' to y'' . This will obviously lead to an increase in the value of $V(\cdot, k)$, for a fixed k . This is captured in the diagram by the positive slope of $V(\cdot, k)$. Now consider the impact of an increase in the quality of information from k' to k'' . This should lead to an increase in the sensitivity of $V(\cdot, k)$. Thus, when the value of the signal increases, $V(\cdot, k)$ should increase by more when the quality of the information is k'' instead of k' . In terms of the diagram, this is depicted by making the curve $V(\cdot, k)$ steeper when the quality of the information improves.

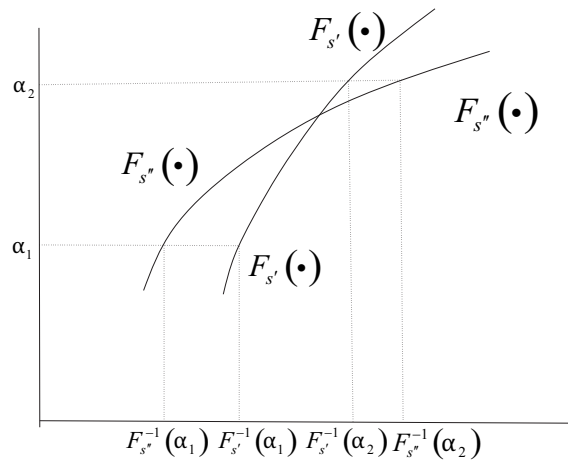


Figure 1: Bickel Lehmann Dispersion

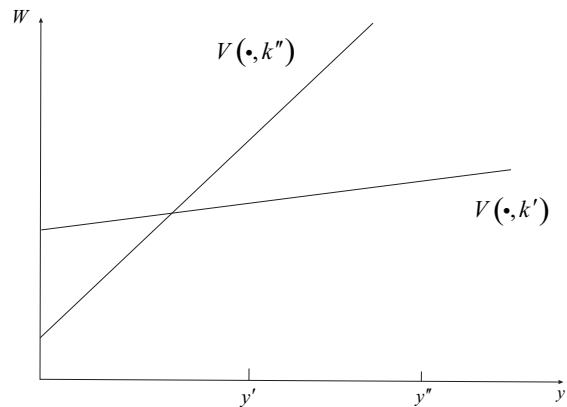


Figure 2: Supermodular Precision

If $V(y, k)$ is a continuously differentiable function, then supermodular precision is equivalent to the following condition:

$$V_{yk}(y, k) \geq 0 \text{ for all } y \text{ and } k. \quad (7)$$

Below, we investigate the restriction that is imposed on the copula function $F^{XY}(x, y; k)$ by (7). This is presented in the lemma below.

Lemma 1 *Supermodular precision imposes the following restrictions on the copula function:*

$$F_{yyk}^{XY}(x, y; k) \leq 0 \text{ for all } y \text{ and } k, \quad (8)$$

and

$$F_{xxk}^{XY}(x, y; k) \leq 0 \text{ for all } x \text{ and } k. \quad (9)$$

Proof. See the Appendix. ■

The above conditions appear in Ganuza and Penalva (2010, p. 1015).

5 Second Period Equilibrium: Screening

For the exposition below, we need to describe two additional terms. The first term is $\hat{\alpha}(y_i)$ and it is the government's estimate of the probability that individual i will attack, given that the government assesses i 's private benefit to be y_i . Therefore, it is given by the following:

$$\hat{\alpha}(y_i) = \int_{x_i=0}^1 \alpha(x_i) f^X(x_i|y_i; k) dx_i, \quad (10)$$

where $\alpha(x_i)$ is the actual probability of attack of individual i . The second term is $\hat{\beta}(x_i)$ and it is i 's estimate that he will be screened, given that i 's actual private benefit is x_i . Hence,

$$\hat{\beta}(x_i) = \int_{y_i=0}^1 \beta(y_i) f^Y(y_i|x_i; k) dy_i, \quad (11)$$

where $\beta(y_i)$ is the actual probability that the government will screen individual i . To anticipate the discussion below, the equilibrium we find is in mixed strategies. In this equilibrium, the government will be indifferent between screening the representative passenger and not screening him, and therefore will randomize between these two actions. Also, the representative passenger will be indifferent between attacking and not attacking, and therefore will randomize between these two actions. We now compute $\beta(y_i)$ below.

5.1 Equilibrium Probability of Screening

Suppose individual i decides to attack. In this case, he either successfully carries out an attack if he is not screened, or he is detected and consequently fails if the government chooses to screen him. The probability that i will be screened is $\hat{\beta}(x_i)$, and in such a case, he is detected and awarded a punishment of z . On the other hand, the probability that he will not be screened is $(1 - \hat{\beta}(x_i))$, and in such a case, i 's *ex post* payoff is x_i . Combining these terms, it follows that the expected payoff of i from carrying out an attack is $[1 - \hat{\beta}(x_i)]x_i - \hat{\beta}(x_i)z$. Further, the expected payoff from not carrying out an attack is 0, since in this case, i neither obtains the private benefit nor the punishment. This leads us to the proposition below.

Proposition 1 *In a mixed strategy equilibrium, i expects to be screened with probability*

$$\hat{\beta}(x_i) = \frac{x_i}{x_i + z}.$$

This expectation is consistent with a government policy that screens i with probability

$$\beta(y_i) = E \left[\frac{x_i}{x_i + z} | y_i; k \right], \quad (12)$$

given an intelligence report of y_i .

Proof. See the Appendix. ■

Notice that, everything else remaining constant, an increase in the punishment z decreases $\beta(y_i)$. This is because an increase in the punishment reduces the additional payoff that individual i obtains from an attack. Further, a uniform screening policy is not the equilibrium outcome in the model. A uniform screening policy would require that two individuals that are alike should be treated in the same way by the government. However, this is not an equilibrium outcome due to at least two reasons. First, the reports about these two individuals may not be identical, and in that case, it is possible that a person with a higher value of y is screened and the other one is not. Interestingly, it is also possible that the person with the lower value of y is screened, while the other one is not. Second, these two persons may not be treated identically even if the intelligence assessments are the same. Since the equilibrium screening policy requires only a fraction of individuals from

each threat category to be screened, therefore, it is possible that only one of these persons may be screened. Thus, in equilibrium, the screening policy may discriminate between individuals who share the same characteristics, but that is an equilibrium phenomenon.

We also need to investigate how the probability of screening changes with a change in the intelligence agency's estimate of i 's private benefit, given by y_i . This is done below.

Lemma 2 *In equilibrium, the government's probability of screening increases with the estimated private benefit y_i , that is, $\beta'(y_i) > 0$.*

Proof. See the Appendix. ■

Below, we determine how $\beta(y_i)$ changes with a change in k . In order to do this, we have to derive two properties of the function $\beta(y_i)$. The first result we are interested in is the value of $\beta(1)$, that is, we determine the probability of screening an individual against whom there is the worst possible (from society's standpoint) intelligence report. This is derived in the following lemma.

Lemma 3 *For $y_i = 1$, the probability of screening is given by $\beta(1) = 1 - z \ln\left(\frac{1+z}{z}\right)$.*

Proof. See the Appendix. ■

Next, we determine how $\beta'(y_i)$ (the slope of the screening function) changes with a change in the expenditure on intelligence gathering. Notice that

$$\frac{\partial \beta'(y_i)}{\partial k} = - \int_{x_i=0}^1 \frac{z}{(x_i + z)^2} F_{y_i y_i k}^{XY}(x_i, y_i; k) dx_i > 0, \quad (13)$$

that is, an increase in the investment in intelligence gathering makes the screening function steeper.

Now, using the above two results, we can show that

$$\frac{\partial \beta(y_i)}{\partial k} = - \int_{y_i}^1 \frac{\partial \beta'(\tilde{y})}{\partial k} d\tilde{y} < 0, \quad (14)$$

that is, the probability of screening goes down for every reported type y_i when there is an increase in the investment in intelligence. The result in (14) demonstrates the importance of better quality intelligence. When the government has better information, then it is more likely the case that the intelligence assessment y_i will be high if the private benefit x_i is high, that is the chance of faulty intelligence is lower. This allows the government to reduce the probability of screening.

Finally, we also consider the impact of an increase in the punishment z . Note from the Appendix that

$$\frac{\partial \beta(y_i)}{\partial z} = - \int_{x_i=0}^1 \left[\frac{x_i}{(x_i + z)^2} \right] f^X(x_i|y_i; k) dx_i < 0, \quad (15)$$

that is, enhanced punishment leads to a reduction in the probability of screening. The intuition for this result is as follows: In the mixed strategy equilibrium, the government makes i indifferent between attacking and not attacking. Now consider an increase in the magnitude of the punishment z . Everything else remaining constant, i now prefers not to attack. In order to make i indifferent again, the government therefore reduces the probability of screening.

The results of this subsection are summarized below.

Proposition 2 *Suppose the government estimates that individual i 's private benefit is y_i . The screening probability $\beta(y_i)$ has the following characteristics:*

- (i) *It is an increasing function of y_i .*
- (ii) *An increase in the intelligence investment k reduces $\beta(y_i)$ and makes the function $\beta(y_i)$ steeper for every y_i .*
- (iii) *It is a decreasing function of the punishment z .*

One might also want to know if there are alternative screening policies of the government other than $\beta(y_i)$ that are also consistent with $\hat{\beta}(x_i)$ (i 's expectation of being screened). The answer is that alternate solutions are possible. However, the deviations of these alternate solutions from $\beta(y_i)$ is purely random and do not have any information content. More specifically, if

$$\tilde{\beta}(y_i) = \beta(y_i) + \epsilon$$

is another equilibrium screening policy, then ϵ is a random variable independent of y_i and $E[\epsilon] = 0$; this has been discussed in detail in the Appendix. Since $\tilde{\beta}(y_i)$ does not have any additional information content, therefore we focus on $\beta(y_i)$ in this paper.

It is also possible to model screening under alternate assumptions. Below, we consider the impact of some alternate assumptions on the model.

5.1.1 Imperfect Detection Technology

Suppose we assume that screening an individual will result in a detection only with probability $p \leq 1$. In this case, the expected payoff of individual i from an attack is

$$\begin{aligned} & \left[1 - \hat{\beta}(x_i)\right] x_i + (1 - p) \hat{\beta}(x_i) x_i - p \hat{\beta}(x_i) z \\ = & \left[1 - p \hat{\beta}(x_i)\right] x_i - p \hat{\beta}(x_i) z, \end{aligned}$$

while i 's payoff from not attacking is still 0. Hence, in equilibrium, the probability that the government will screen an individual given an estimated private benefit of y_i will be $E\left[\frac{x_i}{p(x_i+z)}|y_i; k\right]$. Notice that allowing for an imperfect detection technology is not going to substantially alter the results.

Another possible scenario is one in which the government screens individual i with probability 1 but the rigor of screening depends on y_i . In the Appendix, we discuss this case and show that this is equivalent to our framework.

5.2 Equilibrium Probability of Attack

Suppose the government decides to screen individual i . In this case, if individual i plans an attack, then it will be detected, and thus such a planned attack will fail. Now let us consider the cost that the government will have to incur. In the profiling stage, it would have to incur a cost of k to gather intelligence about individual i . Further, in the screening stage it will have to incur a screening cost of c if it decides to screen individual i . Thus, if the government decides to screen individual i , then no attack occurs and the government incurs an expenditure of $(c + k)$. Thus, the government's payoff from screening i is $u(-c - k)$. Next, consider the outcome if the government decides not to screen i . In such a case, if i decides to attack, then he is not hindered, and thus he inflicts a damage of $L(x_i)$. Further, the government does not have to bear the cost of screening. Consequently, the government's *ex post* payoff is $u(-L(x_i) - k)$ if i attacks and is $u(-k)$ if i does not attack. Hence, the expected payoff of the government is given by

$$\begin{aligned} & P(\text{Attack}|y_i) E[u(-L(x_i) - k)|y_i] + P(\text{No Attack}|y_i) u(-k) \\ = & \hat{\alpha}(y_i) E[u(-L(x_i) - k)|y_i] + [1 - \hat{\alpha}(y_i)] u(-k). \end{aligned} \tag{16}$$

This leads us to the proposition below.

Proposition 3 *In a mixed strategy equilibrium, the government expects an attack with probability*

$$\hat{\alpha}(y_i) = E \left[\frac{u(-k) - u(-c - k)}{u(-k) - u(-L(x_i) - k)} | y_i; k \right]$$

when it receives an intelligence report y_i . This expectation is consistent with i 's strategy to attack with probability

$$\alpha(x_i) = \frac{u(-k) - u(-c - k)}{u(-k) - u(-L(x_i) - k)}, \quad (17)$$

when his private benefit is x_i .

Proof. See the Appendix. ■

There is one crucial difference between the nature of the expressions for $\alpha(x_i)$ and $\beta(y_i)$. The difference is that the expression for $\alpha(x_i)$ depends on x_i which can be observed by i ; thus, this expression is not written as an expected value. On the other hand, $\beta(y_i)$ depends on $\left(\frac{x_i}{x_i+z}\right)$ but x_i is not observed by the government. Thus, $\beta(y_i)$ is expressed as an expected value. The expressions are different primarily because individuals are heterogenous (since there can be different value of the private benefit) but the government is not. Also note that while $\hat{\alpha}(y_i)$ may be consistent with alternate strategies of i , these alternate strategies are purely random perturbations around $\alpha(x_i)$ that are independent of x_i . This can be proved using similar methods as in Appendix C. Therefore, we focus on $\alpha(x_i)$ in this paper.

Let us now examine some of the properties of $\alpha(x_i)$. First, we examine how $\alpha(x_i)$ changes with the private benefit x_i . It follows from (17) that $\alpha'(x_i) < 0$. Thus, a more devious terrorist (that is, one with a higher value of x_i) has a lower probability of attacking. The reason is as follows: In the mixed strategy Nash equilibrium, a terrorist makes the government indifferent between screening an individual and not screening him. The government's payoff from not screening an individual is a constant and does not depend upon the attack probability. Hence to ensure that the government remains indifferent between screening and not screening, the expected damage must remain the same for all values of x_i . Since the actual damage conditional on a successful attack increases with x_i , therefore the probability of an attack must go down with an increase in x_i .

Second, we examine how $\alpha(x_i)$ changes with the screening cost c . It can be shown that $\frac{\partial \alpha(x_i)}{\partial c} > 0$, that is, an increase in the screening cost will induce individual i to attack more often.

Finally, we examine the impact of an increase in the expenditure on intelligence k on the likelihood of an attack. It can be shown that the sign of $\frac{\partial \alpha(x_i)}{\partial k}$ is ambiguous. The intuition is as follows: When the government increases k , then everything else remaining constant, its quality of information increases. Hence, individual i would like to reduce the value of the extra information that the government has. In order to do so, individual i acts in a seemingly random way by reducing the sensitivity of $\alpha(x_i)$ with respect to x_i ; this is achieved by making $\alpha(x_i)$ a flatter function of x_i . As discussed above, $\alpha(x_i)$ is a decreasing function of x_i . That is, for small x_i the attack probability $\alpha(x_i)$ is relatively large, while for large x_i the attack probability $\alpha(x_i)$ is relatively small. Therefore, in order to flatten the function, $\alpha(x_i)$ decreases for small x_i , while it may increase for large x_i . Such a feature may arise in adverse selection models such as this one. A formal derivation of this observation is in the Appendix.

Following the discussion above, we have the following proposition:

Proposition 4 *Suppose individual i 's private benefit from a successful terror attack is x_i . Then, in equilibrium, the probability that individual i will attack, denoted by $\alpha(x_i)$, is given by (17). The attack probability $\alpha(x_i)$ has the following characteristics:*

- (i) *It is a decreasing function of x_i .*
- (ii) *An increase in the screening cost c increases $\alpha(x_i)$ for every x_i .*
- (iii) *An increase in the intelligence investment k has an ambiguous impact on $\alpha(x_i)$; for small values of x_i , an increase in k reduces $\alpha(x_i)$, while for large enough values of x_i , an increase in k **may** increase $\alpha(x_i)$.*

Proof. See the Appendix. ■

Let us now determine the equilibrium payoff of the government in the screening stage of the game. The payoff function in the screening stage is given by (16). We can substitute the equilibrium value of the attack probability to derive the equilibrium payoff of the government and this is formally derived in the Appendix. However, it is possible to derive the equilibrium payoff by using a simple observation viz., that in the screening stage, the equilibrium is in completely mixed strategies. Hence in equilibrium, the government is indifferent between screening and not screening

individual i . Further, its payoff from screening i is $u(-c - k)$. Hence, the equilibrium payoff of the government in the screening stage is simply $u(-c - k)$. As a result, the term $L(x_i)$ drops out from the equilibrium payoff of the government in the screening stage, but this is a consequence of the nature of the equilibrium. In the next section, we use the results of this section to determine the optimal investment in intelligence.

6 Period 1: Optimal Investment in Intelligence

In this model, there are two primary actors: government and individual. The government coordinates security operations. At the same time, the government also considers the opportunity cost of resources spent on security. This opportunity cost arises because money spent on providing security can be alternatively spent elsewhere such as in education or in health, and those competing uses are socially valuable. Apart from the government, there is a representative individual called i in the model. The social welfare function, which could be considered as a goal of a social planner, measures the overall well-being of society. Hence, it includes all social benefits and costs of security, and these are described below.

6.1 Government Payoff in the Screening Stage

First, we consider the payoff of the government in the screening stage. In general, the payoff of the government in the screening stage is given by (16). As discussed above, in the mixed strategy equilibrium of the screening stage, the government is indifferent between screening and not screening i . Hence, in equilibrium, (16) takes the value $u(-c - k)$. Hence, in the welfare function below, we denote the government's equilibrium payoff in the screening stage by

$$G = u(-c - k) \tag{18}$$

which is simply its payoff from screening i .

This implies that if providing security is the government's only concern, then its investment in intelligence gathering should be 0. In the absence of any other concern regarding the cost of security, the government can provide security by screening with probability 1. However, in that

case, the social cost of security may be too high. Intelligence allows the government to focus screening resources on passengers who are likely to be a threat, and hence reduces the cost of providing security. Thus, intelligence is socially valuable only when there are substantial social costs associated with security.

6.2 Social Cost of Security Expenditure

Government while caring for the optimal level of the security also cares for the opportunity cost of the money that is spent in providing security. This opportunity cost arises because if there was no expenditure on security, then resources could have been used for productive purposes in the economy (such as in building infrastructure). In order to determine the opportunity cost of the resources spent in security, we have to first determine the total expenditure on security. The total expenditure is the sum of the expenditure on screening and the expenditure on intelligence. The expenditure on intelligence is k . Therefore to complete the analysis, we need to determine the expenditure on screening and this is done below.

First, we determine the *ex ante* probability of screening i . Since there is one representative individual in this model, therefore, by the law of large numbers (Ramanathan (1993), p. 150), this is equivalent to finding the proportion of selectees (passengers who undergo special screening) when there are a large number of identical passengers who act independently of each other. The *ex ante* probability of screening i is as follows:

$$q(k) = \int_{y_i=0}^1 \beta(y_i) f^Y(y_i; k) dy_i = \int_{y_i=0}^1 \beta(y_i) dy_i$$

since $f^Y(y_i; k)$ is the density of the uniform distribution. Therefore, using (14), it follows that

$$q'(k) = \int_{y_i=0}^1 \frac{\partial \beta(y_i)}{\partial k} dy_i < 0, \tag{19}$$

that is, the *ex ante* probability of screening i decreases with an increase in the investment in intelligence gathering. This can also be interpreted to mean that an increase in the expenditure on intelligence will lead to a reduction in the proportion of passengers who will be screened. The total amount of resources spent in providing security is $cq(k) + k$, where the first term is the expected

screening cost and the second term is the cost of gathering intelligence. Let the opportunity cost of one unit of resource be $\lambda > 0$. This opportunity cost arises because of three reasons. The first reason is that money spent on security could have been spent on other productive uses, and this diversion represents a loss to society. Second, the money for security will usually be raised through taxation. It is well-known that there are deadweight losses associated with taxes, and these deadweight losses represent another cost to society. Third, in a democratic society, screening of passengers represents a loss of privacy and civil liberties and this is another kind of social cost due to screening. However, this kind of social cost plays a much more important role in the analysis of the political aspects of terrorism and therefore we do not specifically focus on this issue in this paper.

The total opportunity cost of all resources spent in providing security is

$$M = \lambda [cq(k) + k]. \quad (20)$$

6.3 Opportunity Cost of Time

In equilibrium, individual i is indifferent between attacking and not attacking. Hence, i 's gross payoff (ignoring any congestion cost) is equal to his payoff from not attacking, which is 0. In order to derive i 's net payoff, we need to determine the value of the congestion externality that is imposed on him because of screening in the airport. The congestion externality can be measured by the opportunity cost of time that is wasted in the airport due to screening. The opportunity cost arises because time spent at the security checkpoint could have been used elsewhere for productive purposes.

Let $\tau > 0$ be the opportunity cost of time required to screen i . In equilibrium, the *ex ante* expected probability of screening the representative passenger is $q(k)$. This can be interpreted to mean that the proportion of selectees is $q(k)$ in a population with a large number of identical passengers who act independently of each other. Hence, the *ex ante* expected congestion externality (that is, the value of time wasted in the security checkpoint) is related to $\tau q(k)$. Since the congestion externality T often increases at a faster rate than the rate of increase of the proportion of selectees,

therefore, we assume that

$$T = T(\tau q(k)); T'(\cdot) > 0 \text{ and } T''(\cdot) \geq 0. \quad (21)$$

In equilibrium, the net payoff of i is given by $-T$.

6.4 Social Welfare

Social Welfare is given by $W = G - M - T$, where G is the equilibrium payoff of the government in the screening stage, M is the equilibrium cost of providing security and T is the congestion externality. Below, we determine the socially optimal level of intelligence expenditure. The optimal investment in intelligence is determined by the solution to the following problem:

$$\underbrace{\max}_k W = u(-c - k) - \lambda c q(k) - T(\tau q(k)) - \lambda k.$$

At this point, we would like to clarify our choice of a two-period model to analyze the optimal allocation of resources between profiling and screening. For the government, it is clear that it would first invest in intelligence and then use that information to screen a given passenger. As for a passenger, there are two kinds of relevant information about the intelligence operation of the government. The first one is the exact report that the government has about the passenger. We assume that only the government is aware of the content of this report. The second piece of information is about the magnitude of the government's investment in intelligence. Note that the optimal level of k is determined by the government by maximizing the welfare function above. Further, the parameters of the welfare function is common knowledge and can be observed by a passenger as well as by the government. Thus, even if the passenger does not observe k directly, he can solve the above problem himself and determine the optimal value of k , just like the government. Thus, it is *as if* the passenger "observes" k (the expenditure on intelligence gathering) before deciding whether or not to attack.

Additionally, there is some evidence that information about k is available, at least in democratic countries. For example, a report by Pam Benson (2010) in CNN informs us that the United States spent \$80 billion on spy activities in 2010. The same report also states that "The government is

required by law to reveal the total amount of money spent to spy on other nations, terrorists and other groups by the CIA, the National Security Agency and the other agencies and offices that make up the 16-member intelligence community.” Regarding UK, we can find from Table 1 of the Spending Review (2010) of the UK government that the expenditure on the Single Intelligence Account was £1.7 billion in 2010-11. Thus, any individual can make a reasonable guess about k , as is assumed in our model.

It follows from the welfare function that the marginal effect of k on the government’s payoff is given by

$$\frac{\partial W}{\partial k} = -u'(-c - k) - (\lambda c + \tau T'(\cdot)) q'(k) - \lambda. \quad (22)$$

Below, we focus on the interior solution. An interior solution cannot exist if the opportunity cost of money λ and the opportunity cost of time τ are both 0. In such a case, note that

$$\frac{\partial W}{\partial k} = -u'(-c - k) < 0,$$

and thus the optimal k would be 0.

In the model, the purpose of intelligence is to determine the risk class of passengers such that resources are directed towards passengers who are more likely to carry out an attack. An improvement in the allocation of resources increases social welfare because of two reasons: First, there is an opportunity cost of resources spent in providing security because such resources could have been used alternatively for productive purposes. In the absence of intelligence inputs, the government will have to screen too many passengers and this may increase the amount of money required for providing security. Second, lack of intelligence inputs means that too many passengers will have to be screened and this will lead to congestion in the airport. Since there is an opportunity cost of time, therefore, there is an additional reduction in social welfare due to congestion. Had the government not cared for the opportunity cost of either money or time spent in security, then, the optimal investment in intelligence gathering would have been 0.

In order to guarantee a unique solution, we also assume that the social welfare function is concave in k , that is,

$$\frac{\partial^2 W}{\partial k^2} = u''(-c - k) - (\lambda c + \tau T'(\cdot)) q''(k) - \tau^2 T''(\cdot) (q'(k))^2 < 0 \quad (23)$$

for all k . By assumption, $u''(\cdot) < 0$ and $T''(\cdot) \geq 0$. Therefore, if $q''(k) > 0$, then $\frac{\partial^2 W}{\partial k^2}$ is guaranteed to be negative. On the other hand, if $q''(k) < 0$, then $\frac{\partial^2 W}{\partial k^2}$ is negative only if $q''(k)$ is small in absolute value.

Let k^* denote the optimal investment in intelligence. The interior solution is described in the proposition below.

Proposition 5 *The socially optimal expenditure on intelligence gathering is given by the solution to the following equation:*

$$u'(-c - k^*) + \lambda = -[\lambda c + \tau T'(\tau q(k^*))] q'(k^*). \quad (24)$$

Let us consider the expression in (24). The left hand side captures the marginal cost of k . An increase in k imposes two kinds of social costs viz. (i) it decreases the payoff of the government in the screening stage, and (ii) it increases the opportunity cost of the expenditure on security. The right hand side of (24) captures the marginal benefit of k . An increase in k reduces the *ex ante* probability of screening since $q'(k^*) < 0$. This reduction benefits society in two ways. First, this reduces the total cost of screening, and this benefits society since such saved resources can be used productively elsewhere. Second, it reduces congestion in the airport, and consequently reduces the waiting time in the airport.

In the next section, we determine the impact on k of changes in certain parameters of the model. Additionally, we also determine how social welfare changes in response to a change in those parameters.

7 Comparative Statics

7.1 Decrease in the unit cost of screening

Suppose there is a decrease in the unit cost of screening c . One would expect that this would allow the government to increase the probability of screening, and this should reduce the value of information, that is, k should decrease. We show below that this conjecture does not always hold.

Below, we examine formally the impact of a decrease in c on the optimal investment in intelli-

gence, given by k^* . By the implicit function theorem and (23), it follows that

$$\text{sign} \left(\frac{\partial k^*}{\partial c} \right) = \text{sign} \left(-|u''(-c - k^*)| + \lambda |q'(k^*)| \right).$$

In general, the sign of the above expression is ambiguous. It follows that $\frac{\partial k^*}{\partial c} > 0$ if and only if

$$\lambda > \frac{|u''(-c - k^*)|}{|q'(k^*)|}.$$

Thus, a reduction in the cost of screening leads to a decrease in the expenditure on intelligence (that is, the above conjecture holds) only when the opportunity cost of resources is sufficiently high.

Why does the conjecture not hold when λ is sufficiently low? In equilibrium, the "bang for the buck" for intelligence expenditure is equalized between the screening stage (Stage 2) and the intelligence gathering stage (Stage 1). Now suppose c decreases. Then, everything else remaining constant, the government's payoff increases in both stages. However, when λ is low, then the government gains relatively more in the screening stage. To restore equality, the government now has to reduce its payoff in the screening stage. This is achieved by increasing k^* . Therefore, $\frac{\partial k^*}{\partial c} < 0$ only when λ is low.

We now examine the impact on welfare of a reduction in the unit screening cost c . A change in c changes social welfare by two means. First, is the direct effect: By Proposition 4, it follows that a reduction in c reduces the probability that individual i will attack, and this reduces the expected loss from an attack. Second, is the indirect effect: A reduction in c changes k^* and this can change social welfare. However, by the first order condition, it follows that $\frac{\partial W}{\partial k} = 0$, and thus the indirect effect has no net impact on welfare. Formally, using the envelope theorem, it follows that

$$\frac{dW}{dc} = \frac{\partial W}{\partial c} + \frac{\partial W}{\partial k} \frac{\partial k}{\partial c} = \frac{\partial W}{\partial c} = -u'(-c - k^*) - cq(k^*) < 0,$$

that is, a decrease in the unit cost of screening unambiguously increases social welfare. Thus, new techniques that reduce the cost of screening increases social welfare, but they may or may not be associated with a reduction in intelligence expenditure.

7.2 Increase in the opportunity cost of time

Suppose there is an increase in the opportunity cost of time τ . First, let us examine the impact of such a change on the optimal investment in intelligence. By the implicit function theorem, (23) and (22), it follows that

$$\text{sign} \left(\frac{\partial k^*}{\partial \tau} \right) = \text{sign} \{ [T'(\cdot) + \tau T''(\cdot) q(\cdot)] (-q'(k^*)) \} > 0.$$

Thus, an increase in the opportunity cost of time leads to an increase in the socially optimal expenditure on intelligence. An increase in the opportunity cost of time means that everything else remaining constant, there is a higher social loss from waiting in a security checkpoint. In order to compensate for this, there has to be a reduction in the waiting time. This can be achieved by increasing k^* . To see the implication of the above result, compare two countries that have identical threat perceptions, but suppose only the first one is a developed economy. In that case, the opportunity cost of time should be higher in the first country, because the opportunity cost is related to wage rates. The above result means that the optimal level of expenditure on intelligence gathering should be higher in the developed country. As an example, this means that even if the United States and Mexico were to face the same level of threats, the optimal level of investment in intelligence should be higher in the United States.

Next, let us consider the impact of an increase in the opportunity cost of time on social welfare. By the envelope theorem, it can be shown that

$$\frac{dW}{d\tau} = \frac{\partial W}{\partial \tau} = -T'(\cdot) q(k^*) < 0,$$

that is, an increase in the opportunity cost of time unambiguously reduces social welfare.

7.3 Increase in the opportunity cost of resources

Suppose there is an increase in the opportunity cost of resources λ . The opportunity cost of the resources spent on security is the value of the most productive alternative use of the resource. It can be measured by the value of the infrastructure or the public programs that have to be given up because resources have to be diverted for the provision of security. Also, some of the money

for security has to be raised by taxes and deadweight losses are often associated with them. These deadweight losses are also part of the opportunity cost of resources used in providing security.

First, let us examine the impact of such a change on the optimal investment in intelligence. By the implicit function theorem and (23), it follows that

$$\text{sign} \left(\frac{\partial k^*}{\partial \lambda} \right) = \text{sign} (-cq'(k^*) - 1).$$

In general, the sign of the above expression is ambiguous. It follows that $\frac{\partial k^*}{\partial \lambda} > 0$ if and only if $c|q'(k^*)| > 1$. When λ increases, then the government would like to reduce the expenditure on security. There are two components of security- intelligence gathering and screening. Suppose the government increases k by \$1. Then the *ex ante* probability of screening decreases by $|q'(k^*)|$ and therefore, the expected screening cost goes down by $c|q'(k^*)|$. If $c|q'(k^*)| > 1$, then the amount saved by reducing the probability of screening is more than the additional expenditure on intelligence gathering. Hence, an increase in k results in a reduction in the total security expenditure, and consequently the government increases k in response to an increase in λ . Applying the same argument, it also follows that the optimal k goes down in response to an increase in λ if $c|q'(k^*)| < 1$.

Second, we examine the impact on social welfare of an increase in the opportunity cost of resources λ . Using the envelope theorem it follows that

$$\frac{dW}{d\lambda} = \frac{\partial W}{\partial \lambda} = -cq(k^*) - k^* < 0,$$

that is, an increase in the opportunity cost of resources unambiguously reduces social welfare.

In the United States, the TSA has instituted a program called PreCheck that allows expedited screening for certain selected assengers. The details about this program can be found in TSA's website as well as in an article by Sharkey (2012) in the New York Times. The passengers who are eligible for this program usually have a high opportunity cost of their time. Passengers who opt into this program voluntarily reveal information about themselves in exchange for expedited screening. Notice that such passengers have a strong incentive to reveal information about themselves since the time that they can save in exchange is highly valuable. On the other hand, the TSA would

not have to spend resources gathering intelligence about them, since, it is as if, they provide this information for free. We can capture some of the effects of this program using our model, although a complete analysis of this program would require a separate paper.

Let us consider appropriate modifications in the welfare function. Suppose the government spends $(k - \epsilon)$ on individual i and the individual voluntarily reveals information worth ϵ . Then, the quality of the information of the government is same as what could have been obtained by spending k without any voluntarily disclosure. Therefore, the welfare function is now as follows:

$$\tilde{W} = u(-c - k) - \lambda c q(k) - T(\tau q(k)) - \lambda(k - \epsilon).$$

Notice that the transformed welfare function \tilde{W} is simply the previous welfare function plus $\lambda\epsilon$. Since the difference is independent of k , therefore it does not affect the marginal incentives. Hence at the optimum, the quality of information of the government is k^* with or without such a program. However, the amount saved clearly represents a social gain. Also note that at the optimum,

$$\frac{d\tilde{W}}{d\lambda} = -cq(k^*) - k^* + \epsilon = \frac{dW}{d\lambda} + \epsilon.$$

Since $0 < \epsilon < k^*$, therefore, $\frac{d\tilde{W}}{d\lambda}$ is still negative. However, $\frac{dW}{d\lambda} < \frac{d\tilde{W}}{d\lambda} < 0$, that is in the presence of the voluntary disclosure program, an increase in the opportunity cost of resources λ still reduces welfare, but by less than what it would in the absence of such a program. Therefore, a voluntary disclosure program cushions the effect of budgetary shortages.

7.4 Increase in punishment

Suppose there is an increase in the magnitude of punishment z ; this punishment is inflicted only if an attack is detected. By the implicit function theorem and (23), it follows that

$$\text{sign}\left(\frac{\partial k^*}{\partial z}\right) = \text{sign}\left\{-[\lambda c + \tau T'(\cdot)]\frac{\partial q'(k^*)}{\partial z} - \tau^2 T''(\cdot)q'(k^*)\frac{\partial q(k^*)}{\partial z}\right\}.$$

In the above expression, the second term is negative because $q'(k^*) < 0$ and

$$\frac{\partial q(k^*)}{\partial z} = \int_{y_i=0}^1 \frac{\partial \beta(y_i)}{\partial z} dy_i < 0.$$

Further, it follows from (15) and (19) that

$$\frac{\partial q'(k^*)}{\partial z} = \int_{y_i=0}^1 \int_{\tilde{y}=y_i}^1 \int_{x_i=0}^1 \frac{x_i - z}{x_i + z} F_{\tilde{y}\tilde{y}k}^{XY}(x_i, \tilde{y}; k^*) dx_i d\tilde{y} dy_i.$$

Thus, $\frac{\partial q'(k^*)}{\partial z} > 0$ if $z \geq 1$, that is if the punishment is strong enough. It therefore follows that $\frac{\partial k^*}{\partial z} < 0$ if $z \geq 1$, that is, any further increase in punishment leads to a decrease in the socially optimal level of intelligence. Below, we describe the reason behind the above result. The term $|q'(k^*)|$ is the effectiveness of intelligence gathering because it measures the reduction in the screening rate in response to an increase in k . When z is initially greater than 1, then an increase in z reduces the effectiveness of intelligence gathering. Hence, it is more efficient to rely on screening than on intelligence gathering in the provision of security. Consequently, in this case k goes down in response to an increase in z .

Next, we examine the impact of an increase in the punishment z on welfare. Using the envelope theorem, it follows that

$$\frac{dW}{dz} = \frac{\partial W}{\partial z} = -(\lambda c + \tau T'(\cdot)) \frac{\partial q(k^*)}{\partial z} > 0.$$

Hence, an increase in punishment unambiguously increases social welfare.

A natural conjecture is that the above result holds because an increase in the magnitude of punishment should reduce the probability of an attack. However, this is not the correct reason behind this result. Notice from Proposition 4 that an increase in z does not change the probability of attack $\alpha(x_i)$ at all. Rather, it follows from Proposition 2 that an increase in z reduces the probability of screening $\beta(y_i)$. Such a reduction has two kinds of social benefit. First, a reduction of screening intensity means that less resources will be required for screening, and the saved resources can be used for productive purposes elsewhere. Additionally, this will also reduce the congestion externality. Thus, welfare goes up in response to an increase in z because of a reduced rate of screening and not because of any reduced probability of attack.

8 Conclusion

In this paper, we focus on efficient ways of providing airport security. There are two processes involved in securing an airport- one is called profiling that is gathering intelligence, and the other one is called screening, that is screening passengers or luggage for weapons. Both of these processes compete for resources. How should resources be optimally allocated between them? If preventing terrorist attacks is the only goal, then intelligence gathering has no role and the job can be accomplished by screening alone. All that is required in this case is to screen every passenger. However, in that case, the total expenditure on security will be quite high, and so will be the waiting times in the security checkpoints. When we consider the value of money as well as of time, then there is a role for intelligence gathering. Indeed, in such a case, profiling and screening are complementary inputs in the provision of security because better intelligence enhances the "productivity" of screening by saving money and time. The reason is that better intelligence allows airport screeners to focus on only individuals who are likely to be a threat and leave out the rest. This reduces the security lines and saves both money and time.

We also determine how the optimal amount of intelligence changes with a change in some key parameters. Suppose there is a cost reducing innovation that reduces the unit cost of screening. One would expect that since screening is less costly now, therefore the value of intelligence should be lower as well and this should reduce the optimal expenditure in intelligence gathering. We find that this intuition is true only when the opportunity cost of resources is high enough. When the opportunity cost of resources is low, then saving money is a far less important concern than the provision of security. Thus, money saved on screening is directed towards enhanced intelligence gathering. On the other hand, when the opportunity cost of resources is high, then saving money is important. Thus, when screening becomes less costly, then the government saves money instead of spending it on intelligence. However, a cost-reducing innovation unambiguously increases welfare.

Next, suppose we compare two countries that face the same kind of threats but differ in their level of economic activity. Then, citizens of the more developed economy are likely to have a higher value of their time. We find that the more developed economy would invest more in intelligence gathering. We also examine the efficacy of a program such as PreCheck that allows some selected passengers expedited screening in exchange for voluntarily revealing information about themselves.

Our analysis shows that such a program can cushion the adverse effect of budgetary shortages.

Finally, we also examine the impact of an increase in punishment on the optimal investment in intelligence. We find that this relationship can go both ways depending upon the initial level of punishment. If the initial level of punishment is too low, then an increase in punishment also increases the optimal investment in intelligence. However, if the initial level of punishment is high, then any further increase reduces the optimal investment in intelligence. We also find that tougher punishment unambiguously increases social welfare by reducing the rate of screening, and not by deterring potential terrorists as one might expect.

This research can be extended to other areas. For example, this paper focuses on passenger security. However, it is equally important to consider cargo security as well as port security. Finally, many acts of terror are perpetrated by transnational terrorists. It is often hard to acquire intelligence about them. It is therefore important to think about the effectiveness of profiling when such loopholes exist. This is left for future research.

References

Babu, V. L., R. Batta and L. Lin (2006). Passenger grouping under constant threat probability in an airport security system. *European Journal of Operational Research* 168(2): 633-644.

Basuchoudhary, A. and L. Razzolini (2006). Hiding in plain sight - using signals to detect terrorists. *Public Choice* 128: 245-255.

Bickel, P.J. and E. L. Lehmann (1976). Descriptive Statistics for Nonparametric Models. III. Dispersion. *Annals of Statistics* 4(6): 1139-1158.

Bier, V. and N. Haphuriwat (2011). Analytical method to identify the number of containers to inspect at U.S. ports to deter terrorist attacks. *Annals of Operations Research* 187(1): 137-158.

Cavusoglu, H., B. Koh and S. Raghunathan (2010). An analysis of the impact of passenger profiling for transportation security. *Operations Research* 58(5): 1287-1302.

Coate, S. and Loury, G.C. (1993). Will affirmative-action policies eliminate negative stereotypes? *The American Economic Review* 83(5): 1220-1240.

Department of Homeland Security (2011). Budget in Brief, fiscal year 2012. Available at <http://www.dhs.gov/xlibrary/assets/budget-bib-fy2012.pdf>.

Ganuza, J.-J. and J. S. Penalva (2006). On Information and Competition in Private Value

Auctions. Working Paper, CEMFI.

Ganuza, J.-J. and J. S. Penalva (2010). Signal orderings based on dispersion and the supply of private information in auctions. *Econometrica* 78(3): 1007-1030.

GTD (2013). Global Terrorism Database. <http://www.start.umd.edu/gtd/>. Accessed March 2013.

Heal, G. and H. Kunreuther (2005). IDS Models of Airline Security. *Journal of Conflict Resolution* 49(2): 201-217.

Jacobson, S. H., L. A. McLay, J. E. Kobza and J. M. Bowman (2005). Modeling and analyzing multiple station baggage screening security system performance. *Naval Research Logistics* 52(1): 30-45.

Jacobson, S. H., T. Karnani, J. E. Kobza and L. Ritchie (2006). A cost-benefit analysis of alternative device configurations for aviation-checked baggage security screening. *Risk Analysis* 26(2): 297-310.

Jackson, B. A., E. W. Chan and T. LaTourrette (2012). Assessing the security benefits of a trusted traveler program in the presence of attempted attacker exploitation and compromise. *Journal of Transportation Security* 5: 1-34.

Krishna, V. (2010). *Auction Theory*. Burlington, MA, Academic Press.

Mas-Colell, A., M. D. Whinston and J. R. Green (1995). *Microeconomic Theory*. New York, Oxford University Press.

McLay, L. A., A. J. Lee and S. H. Jacobson (2010). Risk-Based Policies for Airport Security Checkpoint Screening. *Transportation Science* 44(3): 333-349.

Meng, X. (2011). Enhanced security checks at airports: minimizing time to detection or probability of escape? Working Paper.

Mueller, J. and M. G. Stewart (2011). *Terror, Security and Money: Balancing the Risks, Benefits and Costs of Homeland Security*. New York, Oxford University Press.

Nelsen, R. B. (2006). *An Introduction to Copulas*. New York, Springer.

Nie, X. (2011). Risk-based grouping for checked baggage screening systems. *Reliability Engineering & Safety* 96(11): 1499-1506.

Nie, X., R. Batta, C. G. Drury and L. Lin (2009). Passenger grouping with risk levels in an airport security system. *European Journal of Operational Research* 194 (2): 574-584.

Nie, X., G. Parab, R. Batta and L. Lin (2012). Simulation-based Selectee Lane queueing design for passenger checkpoint screening. *European Journal of Operational Research* 219(1): 146-155.

Nikolaev, A. G., S. H. Jacobson and L. A. McLay (2007). A sequential Stochastic Security System Design Problem for Aviation Security. *Transportation Science* 41(2): 182-194.

Persico, N. and P. E. Todd (2005). Passenger profiling, imperfect screening, and airport security. *American Economic Review* 95(2): 127-131.

Press, W. (2009). Strong profiling is not mathematically optimal for discovering rare malfeasors. *PNAS* 106(6):1716-1719.

Press, W. (2010). To catch a terrorist: can ethnic profiling work? *Significance* 7(4): 164-167.

Ramanathan, R. (1993). *Statistical Methods in Econometrics*. San Diego, Academic Press.

Reddick, S. (2011). Point: The case for profiling. *International Social Science Review* 79, 3 & 4: 154-156.

Sandler, T., D. G. Arce and W. Enders (2008). *The Challenge of Terrorism*, Copenhagen Consensus Center.

Sharkey, J. (May 2, 2012). V.I.P. Treatment Eases the Way Through Security. *New York Times*.

Wang, X. and J. Zhuang (2011). Balancing congestion and security in the presence of strategic applicants with private information. *European Journal of Operational Research* 212(1): 100-111.

Yetman, J. (2004). Suicidal terrorism and discriminatory screening: An efficiency-equity trade-off. *Defence and Peace Economics* 15(3): 221-230.

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