Safety at What Price?: Setting Anti-terrorist Policies for Checked Luggage on US Domestic Aircraft

by

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Abstract

In this thesis, we considered the costs and benefits of implementing Positive Passenger Bag Match (PPBM) - an anti-terrorist measure to keep bombs out of checked luggage - on US domestic passenger flights. We constructed a stochastic model for comparing the cost-effectiveness of three alternative approaches to PPBM: no PPBM implementation; a PPBM imlementation that is applied to 5% of passengers; and a full (100%) implementation of PPBM. We made ranges of estimates concerning the level of terrorist risk, the costs of PPBM operation, the consequences of successful terrorist bombings, and the anti-terrorist effectiveness of both the partial and full PPBM implementations. Calculations showed that there were circumstances under which each policy was the most cost-effective of the three. Of the three options, not implementing PPBM at all was the most cost-effective approach for the largest percentage of the scenarios considered. We found that 5% PPBM captured the next largest portion of the scenarios, and was generally the optimal strategy when annual PPBM operation costs were low, when 5% PPBM anti-terrorist effectiveness was high, and when the consequences of successful bombings were severe. We found 100% PPBM to be the optimal strategy for most scenarios which involved highly costly terrorist bombings, a high level of terrorist risk, and a 100% PPBM policy that provided much added security over 5% PPBM.

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Chapter 1

Introduction

Civil aviation has historically been a target of terrorism. From 1949 to 1989, there were more than 90 explosions aboard civilian aircraft as a result of sabotage.[9] Events in recent years have heightened the Federal Aviation Administration's (FAA's) sensitivity to the threat of terrorism. The 1993 bombing of the World Trade Center, in which approximately 1200 pounds of explosives killed 6 and injured 1042, [6] was a reminder of the sophistication and magnitude of this threat. In 1996, US courts convicted Ramzi Ahmed Yousef and his co-conspirators for their part in a 1995 conspiracy to place explosive devices on twelve US passenger airliners operating in East Asia.[7] According to the FAA, the 1995 conspiracy is evidence that:

> (1) foreign terrorists conducting future attacks in the United States may choose civil aviation as a target, despite the many more easily accessible targets equally symbolic of America;
>
> (2) foreign terrorists have the ability to operate in the United States; and
>
> (3) foreign terrorists are capable of building and artfully concealing improvised explosive devices that pose a serious challenge to aviation security.[2]

Three recent events give us evidence of the severe consequences of in-flight explosions. In 1985, a device exploded in the cargo hold of India Air flight 182, causing it to crash into the ocean near Ireland. This disaster, which killed 329, was attributed to a terrorist who had placed a bomb in luggage he had checked, and who then disembarked at an intermediate stop. In 1988, Pan American Airways (Pan Am) flight 103 was destroyed by the detonation of an explosive device located in the plane's forward cargo hold. The wreckage landed in Lockerbie, Scotland, killing 11, and all 259 people on board were killed. In 1989, a bomb in the forward cargo hold of Union des Transportes Aeriens (UTA) flight 772 exploded, causing the aircraft to crash in the Saharan Desert, killing 171. A Congolese man, who boarded at Brazzaville and got off at Ndjamera, was believed to have been responsible for the blast.[5]

In light of these incidents, the FAA has been exploring various counter-terrorism measures that might mitigate this threat to civil aviation. One possibility the FAA has considered is the use of explosives detection system (EDS) equipment, which would scan checked baggage for explosive devices. EDS equipment, however, is not yet widely available. The FAA has also considered the application of a security measure called Positive Passenger Bag Match (PPBM) to domestic flights. PPBM is already in use on international flights.

Applied properly, PPBM prevents checked luggage from traveling on a flight unless it is known to have been checked by a passenger who is aboard the flight. If, at departure time, airline employees find that an unaccompanied bag is on the flight, PPBM policy dictates the removal of that bag from the airplane (hereafter, a "bag-pull"). Therefore, if a terrorist were to attempt to sabotage an airplane by means of a device in checked luggage, successful PPBM would force him to accompany his bag onto the airplane. He would have to intend on killing himself along with the other passengers. Thus, PPBM potentially serves as both a deterrent and an obstacle to terrorism.

PPBM is standard for virtually all international flights, and is required by the International Civil Aviation Organization (ICAO). Though PPBM is not required for US domestic flights, US carriers currently perform a limited version of PPBM on much of their flight network. The questions that have emerged are: Should PPBM be implemented domestically, and, if so, how exactly? The White House Commission on Aviation Safety and Security requested, in the Fall of 1996, that the FAA explore the optimal method by which to implement PPBM for US domestic flights. In response to this request, The FAA created a PPBM Technical Project Team (hereafter, PTP-T), which included both the National Center of Excellence in Aviation Operations Research (NEXTOR) and the SABRE group. The task set aside for this team was to answer the questions about PPBM implementation posed above, and, in particular, to consider two forms of PPBM implementation: full-implementation, and a partial implementation, which would expose just 5% of passengers to Bag-Match (hereafter, 5% PPBM).

In May 1997, PTPT undertook a two-week Live Test of full domestic PPBM, to obtain an estimate of the costs and delays that a domestic implementation of PPBM would incur. The FAA considered the Live Test results and issued a Report to Congress which included a comparison of "international-style" 100% PPBM and 5% PPBM. In this Report, the FAA stated that the 5% policy would be superior to the 100% policy if cost and operational delays were the only criteria, but that they are not. The FAA remarked that it was not straightforward whether 5% or 100% PPBM was the optimal strategy, and that a policy's optimality depended on the magnitude of the terrorist threat.

In this thesis, we explore the question of whether PPBM should be implemented domestically, and, if so, at which level. Our models consider the long-term economic costs of each of the three policies. The optimality of a PPBM policy depends on assumptions about the underlying terrorist threat, the costs of PPBM implementation, the consequences of terrorist bomb attacks, and the effectiveness of Bag-Match in preventing these attacks. Obtaining results from our models requires that we estimate numerous parameters. We can estimate some of these with accuracy, while other parameters are harder to get a handle on, or are better left estimated by others. Because of this, we do not settle on one set of parameter values, but instead explore the conditions under which one policy is superior to the others. We have taken the approach of making low, middle, and high estimates for each parameter, and constructing a set of what we thought were plausible scenarios based on these estimates.

Our analysis indicates that not implementing PPBM at all is the optimal policy in the largest percentage of the scenarios, followed next by 5% PPBM and then by 100% PPBM. We found that 100% Bag-Match was most cost-effective for a majority of the scenarios in which there was a high risk of terrorism and terrorist attacks were very costly. If we added the assumption that 100% Bag-Match was very effective in preventing terrorist attacks, it became the optimal policy in eight out of nine scenarios. Our models indicated that 5% PPBM was most cost-effective for a majority of cases in which PPBM operational costs were low and 5% PPBM was extremely effective. If it was also the case that successful terrorist attacks were extremely costly, 5% PPBM performed substantially better. Finally, we found that the optimality of not implementing Bag-Match at all was highly dependent upon our assumptions about the effectiveness of the 5% Bag-Match policy.

In section 1.1, we describe, in more detail, PPBM, the Live Test organized by PTPT, and the current state of affairs regarding PPBM implementation. In section 1.2, we state the assumptions under which our models operate and the conventions we will use throughout the thesis. In sections 1.3 and 1.4, we introduce two probabilistic models, one in each section, and use them to derive equations for the comparison of Bag-Match policy cost-effectiveness. We compare and contrast these models in section 1.5, and set about estimating the parameters for the models and constructing our set of scenarios in section 1.6. We explore the results from our models in section 1.7, and provide a discussion of caveats in section 1.8. We end with a summary of our analysis and conclusions in section 1.9.

1.1 PPBM, the Live Test, and the Present Policy

1.1.1 PPBM

As we have mentioned, the aim of PPBM is to prevent unaccompanied checked luggage from traveling on passenger aircraft. To accomplish this aim, it is necessary to: (1) prevent the loading of luggage that is not associated with any passenger, and (2) remove luggage that was checked by a passenger who is not present on the aircraft at flight time (a bag-pull). Delays can result from verifying that each bag is properly matched with a passenger on board, and from a bag-pull in the case that a bag is not properly matched. PPBM must also contend with the case of connecting passengers, who, if they had checked luggage, would cause a bag-pull by disembarking at an airport that is not their final destination.

The 5% Bag-Match policy (hereafter, 5% PPBM) uses passenger profiling to identify 5% of passengers as "high-risk" and subjects them to PPBM, while the remaining passengers do not receive such scrutiny. The intent of passenger profiling is to cut down on PPBM implementation costs and baggage-pull delays, while retaining many of the security benefits of full PPBM implementation. The effectiveness of passenger profiling hinges, of course, on how well dangerous passengers can be singled out.

1.1.2 Results from the Live Test

The PTPT decided to undertake a two-week Live Test of domestic PPBM in order to obtain better estimates of the costs and benefits of PPBM implementation. NEXTOR was largely responsible for the design, administration, and observation of the test, which involved eleven airlines, 8,000 flights, and nearly 750,000 passengers, and delivered a full report of the Live Test to the FAA. A detailed description of the conditions and results of the Live Test can be found in Barnett et al. [4]

Based on this experiment, NEXTOR projected that a full implementation of PPBM would delay roughly 1/7 of the flights, with the average delay being about seven minutes. NEXTOR found that PPBM would cost the airlines approximately $0.40 per passenger enplanement. Although the Live Test only emulated 100% PPBM, NEXTOR was asked by the FAA to comment on the costs we might expect 5% PPBM to incur. Barnett et Al. gave a "rule-of-thumb that delays drop about 75% and costs drop about 50%" as we move from 100% PPBM to 5% PPBM, but pointed out the serious difficulties one encounters in attempting to estimate the 5% PPBM costs from the 100% PPBM data.

1.1.3 Current State of Affairs

Before the Live Test, in February 1997, the White House Commission on Aviation Safety and Security made the initial recommendation that the FAA should implement PPBM by December 31, 1997, and that this implementation should be based on passenger profiling. [8] After the Live Test, NEXTOR delivered a full report of the experiment to the FAA.

The FAA considered the Live Test results in turn, and issued a Report to Congress which included a comparison of "international-style" 100% PPBM and 5% PPBM. In this Report, the FAA stated that the 5% policy would be superior to the 100% policy if cost and operational delays were the only criteria, but they are not. Still, as is evidenced by the following quote, the FAA concluded that the additional security provided by 100% PPBM over 5% PPBM did not justify the added cost and inconvenience:

> Based in part on the result of [NEXTOR's] study, the FAA believes that a domestic 100% PPBM requirement is not the most feasible approach ... Given the present level of domestic threat, the FAA believes that, bag-matching of passengers selected by a FAA-approved computer-assisted passenger screening (CAPS) system is better suited for domestic civil aviation operations.[1]

In this same report, the FAA describes its plans for PPBM policy:

> "The FAA will soon be proposing a rule entitled *Security of Checked Baggage on Flights Within the United States* [FAA's emphasis] which will address [sic] FAA's goal to enhance checked baggage security measures for domestic flights. The proposed rule will require U.S. carriers using larger aircraft, to apply CAPS to all passengers."

To date, the FAA has not made 5% PPBM the required policy, even for passengers on larger aircraft. Most US airlines do currently apply 5% PPBM to their domestic travelers, however. For example, the author was subjected to PPBM while flying from San Francisco to Boston in March 2000.

1.2 Model Assumptions

1.2.1 Conventions and Assumptions

We proceed under the following conventions/assumptions:

(A1) We define an *attack* as the attempt of a terrorist or terrorist group to detonate one or more explosive devices in checked luggage on one or more US domestic, commercial flights. We will describe an attack as *successful* if it results in at least one fatality.

In this study, we are primarily concerned with the terrorist attack process that will be directly impacted by the Bag-Match security measure. This threshold for an attack's success (i.e. causing at least one fatality) reflects our decision to focus on effective terrorist attacks. If, for example, we were to label as "successful" an attack which merely damages the interior of a plane's bathroom, we would be considering an incident in which the costs are several orders of magnitude fewer than for an attack which causes fatalities.

(A2) Absent PPBM, future successful attacks will occur according to a Poisson Process with rate λ.

The Poisson Process is a natural representation for events which occur randomly over time at a fixed average rate. λ is interpreted as the average number of successful attacks that will occur in a year in the future.

(A3) We consider three levels of PPBM implementation: 100% PPBM; 5% PPBM with passenger profiling; and no implementation of PPBM.

To simplify notation, we will henceforth refer to "no PPBM implementation" as "0% PPBM." Let $i \in I, I = \{0, 5, 100\}$ be the indices corresponding to these three levels.

(A4) We take k_5 to be the conditional probability that an attack which would have been successful under 0% PPBM, is still successful despite the operation of 5% PPBM.

PPBM can serve to deter a terrorist who is planning an attack, and to foil an attack that is actually attempted. This probability incorporates both of these aspects of attack prevention for 5% PPBM.

(A5) We assume that 100% PPBM is at least as effective at preventing attacks as 5% PPBM, and that 5% PPBM is at least as effective as 0% PPBM. We take γ_{100} to be the conditional probability that an attack which would have been successful under 5% PPBM, is still successful despite the operation of 100% PPBM.

We are modeling the process of successful attacks under i% PPBM, $i = 5, 100$, as a Bernoulli splitting of a Poisson process, and, from probability theory, follows a Poisson distribution with respective rates λk_5 and $\lambda k_5 \gamma_{100}$. We are thus assuming the existence of one underlying terrorist attack process, rather than three independent Poisson processes with different rates. Note that the chance of an attack's success under 100% Bag-Match, which is the product of k_5 and γ_{100}, cannot exceed the chance of its success under 5% Bag-Match, k_5.

(A6) Let B_i be the yearly cost of maintaining an i% PPBM policy, not including set-up costs. We treat $B_0 = 0$ and we assume $B_0 \leq B_5 \leq B_{100}$.

(A7) We assume that the start-up costs of PPBM are negligible when compared to its recurrent costs.

(A8) Let C_i be the cost of a successful attack, given that the airline was using i% PPBM at the time of the attack.

This cost has three components: the costs of compensation paid to the families of people killed in the attack (which are often tied to major litigation), the cost of damages to the aircraft, and the loss of passenger revenue in the wake of the successful attack because some people will be frightened away from flying. (As we will see later, these costs are difficult to estimate.)

1.2.2 Policy Adjustment Assumptions

In evaluating a process over a long time horizon, it is critical for us to consider both the current process and any events that might precipitate changes in that process. In particular, we are concerned with any PPBM policy changes that the FAA might undertake in response to successful attacks. We consider two scenarios, which represent the extremes of FAA response:

(1) The FAA decides to leave in place the same PPBM policy that had been in operation at the time of the successful attack. (hereafter, the "static" assumption)

(2) Immediately following the first successful terrorist attack, the FAA requires airlines to implement 100% PPBM if it was not already in place. (hereafter, the "dynamic" assumption)

In this analysis, we develop two different models, one which operates under the static assumption (the "static model"), and another which operates under the dynamic assumption (the "dynamic model").

1.3 Static Model

If we assume that there are no policy changes in response to successful attacks, our model is straightforward. Let L_i be the expected yearly cost of i% PPBM. For a Poisson process, the expected number of arrivals in a period of length 1 unit is just the rate of that process. Since the 5% and 100% processes are split Poisson processes, with respective rates λk_5 and $\lambda k_5 \gamma_{100}$, we find that:

$$
\begin{aligned}
L_0 &= B_0 + \lambda C_0 && (1.1)\\
L_5 &= B_5 + \lambda k_5 C_5 && (1.2)\\
L_{100} &= B_{100} + \lambda k_5 \gamma_{100} C_{100} && (1.3)
\end{aligned}
$$

Comparing the long-term expected cost of each policy for this model is equivalent to comparing among L_0, L_5, and L_{100}. Let us say that policy i "dominates" policy j if policy i is strictly cheaper than policy j in a long-term expected cost sense. For the static policy, i% PPBM dominates j% PPBM if $L_i < L_j$. A PPBM policy is optimal if and only if it dominates the other two PPBM policies. We note the inherent transitivity in such comparisons (i.e. if i% PPBM dominates j% PPBM, and j% PPBM dominates k% PPBM, then i% PPBM dominates k% PPBM).

1.4 Dynamic Model

If we assume that the FAA requires a switch to 100% PPBM when there is a successful attack under the less strict PPBM policies, the picture becomes more complicated. Let us consider a period of length T, where $T \gg 0$. For T sufficiently large, we can be sure that a successful attack will occur during that period regardless of the level of PPBM implementation (in fact, for the subsequent equations to hold, we only need this to be true for the 0% and 5% policies). Let $\Delta_{i,j}$ be the expected cost of j% PPBM over a period of length T minus the expected cost of i% PPBM over that same period. Let t_i be the time of the first successful attack under i% PPBM. The expected value of t_0 is $1/\lambda$, since its distribution is exponential with rate λ. Therefore,

$$\Delta_{0,100} = T(B_{100} + \lambda k_5 \gamma_{100} C_{100}) - [\frac{B_0}{\lambda} + C_0 + (T - \frac{1}{\lambda})(B_{100} + \lambda k_5 \gamma_{100} C_{100})], \quad (1.4)$$

where the first term in the equation represents the expected cost incurred over time T with 100% PPBM in operation, and the second term represents the sum of the cost incurred over time $1/\lambda$ under 0% PPBM, the successful attack under 0% PPBM, and the cost incurred over time $T - 1/\lambda$ under 100% PPBM, in that order. Note that this first term is drawn directly from equation 1.3.

We see that 0% PPBM dominates 100% PPBM when $\Delta_{0,100} > 0$, or, equivilently, when:

$$\begin{aligned} T(B_{100} + \lambda k_5 \gamma_{100} C_{100}) &> \frac{B_0}{\lambda} + C_0 + (T - \frac{1}{\lambda})(B_{100} + \lambda k_5 \gamma_{100} C_{100}) \\ 0 &> \frac{B_0}{\lambda} + C_0 - \frac{B_{100}}{\lambda} - k_5 \gamma_{100} C_{100} \\ B_{100} + \lambda k_5 \gamma_{100} C_{100} &> B_0 + \lambda C_0 \qquad (1.5) \end{aligned}$$

Refering back to equations 1.1 and 1.3, we see that our evaluation of the relative cost-effectiveness of 0% and 100% PPBM is independent of which model we use.

Let us now compare 5% and 100% PPBM, noting that $E[t_5] = 1/(\lambda k_5)$.

$$\Delta_{5,100} = T(B_{100} + \lambda k_5 \gamma_{100} C_{100}) - [\frac{B_5}{\lambda k_5} + C_5 + (T - \frac{1}{\lambda k_5})(B_{100} + \lambda k_5 \gamma_{100} C_{100})], \tag{1.6}$$

where we have the same structure as in equation 1.4.

Thus 5% PPBM dominates 100% PPBM when:

$$\begin{aligned} T(B_{100} + \lambda k_5 \gamma_{100} C_{100}) &> \frac{B_5}{\lambda k_5} + C_5 + (T - \frac{1}{\lambda k_5})(B_{100} + \lambda k_5 \gamma_{100} C_{100}) \\ 0 &> \frac{B_5}{\lambda k_5} + C_5 - \frac{B_{100}}{\lambda k_5} - \gamma_{100} C_{100} \\ B_{100} + \lambda k_5 \gamma_{100} C_{100} &> B_5 + \lambda k_5 C_5 \end{aligned} \tag{1.7}$$

From this result, and equations 1.2 and 1.3, we see that our comparison equation is again independent of model.

Finally, we compare the 0% and 5% PPBM policies under the dynamic model:

$$\begin{aligned} \Delta_{0,5} = [\frac{B_5}{\lambda k_5} + C_5 + (T - \frac{1}{\lambda k_5})(B_{100} + \lambda k_5 \gamma_{100} C_{100})] \\ - [\frac{B_0}{\lambda} + C_0 + (T - \frac{1}{\lambda})(B_{100} + \lambda k_5 \gamma_{100} C_{100})] \end{aligned} \tag{1.8}$$

We see that 0% PPBM dominates 5% PPBM when $\Delta_{0,5} > 0$, or, equivalently, when:

$$\begin{aligned} [\frac{B_5}{\lambda k_5} + C_5 + (T - \frac{1}{\lambda k_5})(B_{100} + \lambda k_5 \gamma_{100} C_{100})] \\ > [\frac{B_0}{\lambda} + C_0 + (T - \frac{1}{\lambda})(B_{100} + \lambda k_5 \gamma_{100} C_{100})] \end{aligned} \tag{1.9}$$

$$\frac{B_5}{k_5} + \lambda C_5 - \frac{B_{100}}{k_5} - \lambda\gamma_{100}C_{100} > B_0 + \lambda C_0 - B_{100} - \lambda k_5\gamma_{100}C_{100}$$

$$\frac{B_5}{k_5} + \lambda C_5 + (k_5 - 1)(\frac{B_{100}}{k_5} + \lambda\gamma_{100}C_{100}) > B_0 + \lambda C_0 \qquad (1.10)$$

In equation 1.10, we see our dynamic model first deviate from the static model. We note the presence of three terms, B_{100}, C_{100}, and γ_{100}, which were not present in equations 1.1 or 1.2. In the comparison of 0% and 5% PPBM under the static model, terms that are associated with 100% PPBM do not enter the equation (no pun intended) because we assume that airlines will not switch to 100% PPBM at any point. We find these terms in the dynamic model, however, due to fact that we expect the first successful attack, and therefore the switch to 100% PPBM, to occur earlier under 0% PPBM than under 5% PPBM, if $k_5 < 1$. We can see this clearly by considering a specific scenario. Let us assume that we have decided not to implement PPBM. Let us also assume that the first successful attack occurs after t_0 years without PPBM implementation. Had 5% PPBM been in operation instead, we would expect this very attack to succeed with probability k_5. If the attack were prevented by 5% PPBM, 5% PPBM would remain in operation until an attack proved successful. It is the potential difference between t_0 and t_5 that introduces an implicit consideration of the 100% PPBM policy parameters. We expect to have 100% PPBM in operation for a longer period of time under 0% PPBM than under 5% PPBM, so the costs of 100% PPBM must enter the picture.

1.5 Model Comparison

1.5.1 Equivalence

Here we explore the conditions under which our static and dynamic models yield the same equation for comparing the 0% and 5% PPBM policies. In doing so, we will have determined the parameter constraints under which the static and dynamic models yield an identical set of policy optimality conditions, due to the fact that the models give us identical equations for comparing 0% to 100% PPBM, and 5% to 100% PPBM.

In the simple case of $k_5 = 1$, which corresponds to 5% PPBM adding no additional attack prevention, we find that the equation for dominance of 0% PPBM over 5% PPBM is identical under each model. Setting $k_5 = 1$ in the comparison of equation 1.1 and equation 1.2, as well as in equation 1.10, yields:

$$B_5 + \lambda C_5 > B_0 + \lambda C_0 \tag{1.11}$$

Intuitively, when $k_5 = 1$ for the dynamic model, we will find that $t_0 = t_5$, and the switch to 100% PPBM will occur at the same time under each policy. We are essentially comparing the expected costs of the two policies up to that switch, so none of the parameters for 100% PPBM are present in equation 1.11. In the more plausible case of $k_5 < 1$, we need to look for parameter values that will make equation 1.10 equivalent to the static model comparison equation:

$$B_5 + \lambda k_5 C_5 > B_0 + \lambda C_0 \tag{1.12}$$

By inspection, for equations 1.10 and 1.12 to be equivalent, we need the following to hold true:

$$\begin{aligned}
B_5 + \lambda k_5 C_5 &= \frac{B_5}{k_5} + \lambda C_5 + (k_5 - 1)(\frac{B_{100}}{k_5} + \lambda \gamma_{100} C_{100}) \\
0 &= (k_5 - 1)[\frac{B_{100}}{k_5} + \lambda \gamma_{100} C_{100} - \frac{B_5}{k_5} - \lambda C_5] \\
0 &= \frac{B_{100} - B_5}{k_5} + \lambda(\gamma_{100} C_{100} - C_5) \qquad (1.13)
\end{aligned}$$

We see that, for our two models to yield equivalent results, we need either $k_5 = 1$

(from before), or $B_5 = B_{100}$ and $C_5 = \gamma_{100}C_{100}$. Let us try to give some intuition for equation 1.13. If $B_5 = B_{100}$ and $C_5 = \gamma_{100}C_{100}$, the 5% and 100% PPBM policies have the same yearly maintenance cost, and the same expected yearly cost due to successful attacks, since it will be true that $\lambda k_5 C_5 = \lambda k_5 \gamma_{100} C_{100}$. In an expected cost sense, then, the 5% and 100% PPBM policies are identical, so our comparison of the expected costs of 0% PPBM to 5% PPBM becomes a comparison of 0% PPBM to 100% PPBM, which is the same for both the static and dynamic models.

1.5.2 Inconsistency

These results imply that, for a given set of parameters, we might find that our static model and dynamic model differ on which PPBM policy is optimal. Furthermore, this difference can only occur if the disputed optimal policies are 0% and 5% PPBM. This is easy to see. Let us assume that the dynamic model gives 100% PPBM as optimal. Since the conditions for dominance of 100% PPBM over 0% PPBM and for 100% PPBM over 5% PPBM are identical under each model, 100% must have a lower expected cost than both 0% and 5% PPBM under the static model as well. The reverse direction is true since we could have simply replaced "dynamic" with "static" and "static" with "dynamic" in the short proof above.

1.6 Parameter Estimation

1.6.1 The Method

To obtain results from these models, we must first estimate numerous parameters. Unfortunately, it is quite difficult to get accurate estimates for most of these parameters. As a result, we have avoided the straightforward, but myopic, method of assigning a single estimate to each parameter, and calculating the optimal PPBM policy from this single set of estimates. Instead, we have taken the approach of estimating a range of values for a given parameter. In particular, we choose a high, middle, and low estimate for each parameter. We then consider each possible combination of parameter estimates as one scenario. For example, one scenario might consist of the high λ estimate, the low B_{100} estimate, the middle k_5 estimate, and so on. We then use our PPBM policy dominance equations to determine, for both the static and dynamic models, which policy is optimal under each parameter scenario. From this analysis, we obtain the percentages of the scenarios for which each PPBM policy is optimal, under each model. A similar approach for coping with parameters that are difficult to estimate can be found in [3].

1.6.2 The Parameters

First and foremost, we consider the issue of estimating λ, the yearly rate of successful, domestic terrorist attacks which involve explosives in checked luggage. It is natural to turn immediately to the historical rate of such incidents. We find that the last successful attack of this type occured in 1955, on United Air Lines flight #629 from Denver to Seattle. It would be difficult to accurately estimate λ based on this single incident. In addition, looking at data before 1955 is of limited use, as the number of domestic flights is orders of magnitude larger today than it was then. We thus look to the historical record for international flights. Drawing on a variety of sources, we have compiled a list of acts of aggression by terrorists on US and international civil aviation from 1950-1999. In this list, found in Appendix A, we include only incidents which resulted in at least one fatality and were confirmed or assumed to have been caused by explosive devices in checked luggage. Seven of these eight incidents involved international flights. Currently, approximately half of all flights are US domestic flights, so we could imagine basing our estimate of λ on the rate of incidents among flights that are not US domestic. This rate, based on Appendix A, is 0.14 incidents per year (7 incidents over 50 years). Based on this logic, we could imagine a λ as low as 0.02 (1 incident in 50 years) or as high as 0.14. We take these two values to be our low and high estimates for λ, and their midpoint, 0.08 incidents/year, to be our middle estimate.

We next look to the Live Test results in order to estimate B_5 and B_{100} (we assumed $B_0 = 0$). NEXTOR estimated that 100% PPBM would cost airlines somewhere between \$0.25 and \$0.52 per emplanement. This corresponds to an expense of \$0.38 to \$0.65 per emplanement for additional staff, automation technology, and flight delays, and a credit of \$0.13 per emplanement for the reduction in baggage mishandling. Based on the FAA projection of 656.5 million US domestic emplanements during the year 2000 [10], the annual dollar cost corresponding to this cost range is \$164 to \$341 million dollars. We take those extremes to be the low and high estimates, and their mean, \$252.5 million, to be the middle estimate.

Although the Live Test involved only 100% PPBM, NEXTOR was also asked to estimate the costs of 5% PPBM. It does not suffice, of course, to arrive at a range for B_5 by dividing the estimated range for B_{100} by twenty. For instance, an airline might choose to invest in automatic boarding-pass readers in order to implement 100% PPBM, but not for a 5% PPBM implementation. After citing this and other estimation difficulties, Barnett et al. proceeded to estimate that costs under 5% PPBM would fall to a range of \$0.07 to \$0.36 [4]. This range corresponds to, under the projection of 656.5 million domestic emplanement per year, a yearly cost ranging from \$46 to \$236 million. We take the midpoint of that range, \$141 million, to be our middle estimate.

We next tackle the task of estimating the cost of a successful attack under the three PPBM policies, C_0, C_5, and C_{100}. This cost is composed of the damage inflicted upon the aircraft, the payments resulting from various lawsuits, and the drop in ticket sales due to potential airline passengers' fear of terrorism. Some of these costs are dependent upon the security policy that was in place at the time of the successful attack. While we have no reason to believe that the cost of the damage to the aircraft will be any different under different PPBM policies, we might expect legal settlement costs to be lower for an airline that was using 100% PPBM ("doing all that it could") rather than 0% PPBM, all else equal. On the other hand, perhaps the drop in ticket revenue would be larger for a successful attack under 100% PPBM than under the two less-strict policies. This could result from a passenger thinking the following, if 100% had been in operation at the time of the attack: "The airlines were doing all they could, and the terrorists still succeeded. I will take the train from now on." Any assumptions about the differences between C_0, C_5, and C_{100} would be highly speculative. Indeed, we have just presented possible scenarios for which the loss of ticket revenue would be more costly, but the legal costs smaller, for C_{100} than for C_0 or C_5. Therefore, we have decided to operate under the assumption that $C_0 = C_5 = C_{100}$, neither due to precise analysis nor because we think that this is actually the case, but because we do not have convincing evidence for alternatives. Let $\tilde{C} \triangleq C_0 = C_5 = C_{100}$.

These costs are also highly dependent on the magnitude of the incident. In particular, we are concerned with estimating the costs which result from the explosion of a device that was brought onto the plane via checked luggage. If we consider the eight such events from Appendix A, we find that in six cases, all people aboard the plane were killed, and in another, just one passenger, who fell 15,000 feet in the tailsection, survived. In the remaining incident, two explosions occurred while the aircraft was on the ground, killing two and severely damaging the aircraft. When we make our estimates for $\tilde{C}$, we bear in mind the severity of the consequences of these eight incidents. There is also the possibility of a terrorist group orchestrating the destruction of multiple aircraft. Indeed, the aforementioned Yousef plot involved plans to place explosive devices on twelve US passenger airlines. Our high estimate for $\tilde{C}$ will be based on a hypothetical incident which results in the destruction of multiple aircraft. To formulate our estimates for $\tilde{C}$, we will first lay the framework for estimating each of the cost components, and then arrive at the low, high, and middle estimates based on that framework.

First let us consider the expected cost of resulting lawsuits. The 1988 crash of Pan Am flight 103 is a logical first stop for this estimation. As I mentioned in the Introduction, 270 were killed in the crash: 243 passengers, 16 crew, and 11 on the ground.[14] A 1996 article by the Associated Press states that "So far, Pan Am has paid an estimated $500 million in damages, and about 20 more cases are pending, according to lawyers for American victims." [15]

The second component of the C_is is the loss of revenue in the wake of the incident. This loss has two sources: airlines will lower fares to attract a more reluctant set of customers and some customers will decide not to fly at all, despite the fare reductions. In 1997, US domestic passenger revenue was approximately \$80 billion. [11] The Air Transport Association predicts approximately 10% more passenger enplanements for 2000 than 1997 [12], and we will estimate \$90 billion to be the annual domestic revenue figure for the year 2000. It is difficult for us to estimate the loss of revenue due to airline crashes from historical data, due to the presence of substantial noise. Perhaps we could get a reasonably accurate figure for Pan Am's loss of revenue in the years subsequent to the crash, but much of that revenue went into the coffers of British Airways. Some passengers might, in effect, boycott the carrier involved in an incident, but give their business freely to another carrier. However, this obfuscates the picture, as we are interested in the system-wide costs. In addition, there is the issue of measuring how long these effects might last. Faced with these difficulties, we prefer to take the, again highly-speculative, approach of estimating percentage losses of the annual, US domestic flight revenue estimate for the year 2000.

Finally, we turn to the cost of the damage to the aircraft. In seven of the eight checked luggage incidents from Appendix A, the airplane itself was destroyed. In the other incident, the plane was severely damaged. In May, 2000, the range of prices for Boeing's commercial aircraft is from \$33 to \$202 million [13], so we will take the average cost of an aircraft to be approximately \$100 million. A more accurate estimate would, of course, analyze what proportion of the US domestic fleet each aircraft constitutes, and the average depreciation on US domestic aircraft.

Let us now compose our high, low, and middle estimates for $\tilde{C}$, in that order. Pan Am flight 103 crashed twelve years before the composition of this thesis, and the last twenty lawsuits to be resolved could very well be the most expensive. For an incident that involved two or three planes, we could therefore conceive of legal fees and lawsuit settlements amounting to two billion dollars. For that same incident, we would expect there to be substantial media coverage of the incident, which would lead to a large loss of revenue. However, it would be hard to imagine a loss greater than 5% of the annual revenue, which comes to \$4.5 billion. Adding in the cost of multiple aircraft, we could imagine \$7 billion for the high estimate of $\tilde{C}$.

For the low estimate of $\tilde{C}$, let's examine the case of the Middle East Airlines airplane which exploded on the ground at Beirut. Two were killed when two parcels exploded as luggage was being off-loaded from the aircraft. We could imagine an incident of this magnitude resulting in costs from aircraft damage and lawsuits of \$200 million, and additionally, an annual revenue loss of a third of a percent. This comes to \$500 million, and we use this for our low estimate of $\tilde{C}$. Finally, a moderate incident might destroy the aircraft, involve lawsuit-related costs of \$750 million, and cause a drop in ticket revenue of one percent of annual domestic revenue. We take this sum, \$1.75 billion, to be our moderate estimate for $\tilde{C}$. To summarize, our high, low, and middle estimates for $\tilde{C}$ are, respectively, \$7 billion, \$500 million, and \$1.75 billion dollars.

There are two parameters that remain to be estimated: k_5 and γ_{100}. k_5, again, is the probability that an attack which would have been successful under 0% PPBM, will also be successful despite the operation of 5% PPBM. γ_{100} is the probability that an attack which would have been successful under 5% PPBM, will still be successful despite the operation of 100% PPBM. Note that both k_5 and γ_{100} are between zero and one. $k_5 = 1$ corresponds to 5% PPBM providing no more security than does 0% PPBM. Likewise, $\gamma_{100} = 1$ corresponds to 100% PPBM providing no more security than does 5% PPBM. Unlike many of the other parameters, k_5 and γ_{100} can not be estimated from historical data. Even if, for instance, another country had implemented 5% PPBM in the past, it would be near impossible to get an accurate idea of the number of terrorists who were *deterred* solely from the operation of 5% PPBM. For lack of a more methodical alternative, we consider a few reasonable scenarios, and base our estimates on those scenarios.

Let our first scenario consist of eight terrorist attacks via checked luggage that would have been attempted and successful under 0% PPBM over some time interval. We ask ourselves the question, "How many of these would have been deterred or foiled by 5% PPBM?" If 5% PPBM were highly effective, the answer might be "six." If 5% PPBM were ineffective, maybe only one attempt would be deterred or foiled. If 5% PPBM were moderately effective, we could imagine that it would deter or foil three

	Low Estimate	Middle Estimate	High Estimate
λ	0.02 incidents/year	0.08	0.14
B_5	\$46 million/year	\$141 mil.	\$236 mil.
B_{100}	\$164 million/year	\$252.5 mil.	\$341 mil.
C_0, C_5, C_{100}	\$500 million/incident	\$1.75 bil.	\$7 bil.
k_5	0.25	0.5625	0.875
γ_{100}	0.125	0.5	0.875

Table 1.1: Range of Estimates for Parameter Values

or four events. The k_5 values corresponding to these statements are 0.25, 0.875, and 0.5625, and we will make these our estimates for k_5.

Now consider eight terrorist attacks via checked luggage that would have been attempted and successful under 5% PPBM. How many of these would have been deterred or foiled by 100% PPBM? We put forth one, four, and seven as our low, middle, and high responses to that question. Based on these responses, our estimates for γ_{100} are 0.125, 0.5, and 0.875.

A summary of these results can be found in Table 1.1.

At this point, I would like to once again emphasize that our methods of estimation are highly approximate, as the reader has observed. Indeed, if the reader feels strongly that one or more estimates were substantially inaccurate, she is invited to revise those estimates and use the equations we have provided to obtain her own results and conclusions. Finally, if the reader has hands-on experience in aviation safety, she is particularly well-positioned to bring that experience to bear on the parameter estimation procedure, and we would encourage her to do so.

1.7 Results

1.7.1 Method

It is evident that we can determine which PPBM policy is optimal for a given set of parameters, under either of the models we have presented. We examined numerous scenarios, composed from the high, low, and middle parameter estimates, seeking to gain an understanding of how each Bag-Match strategy performed overall, and which

	0% PPBM	5% PPBM	100% PPBM
Static Model	69.5%	16.5%	14.0%
Dynamic Model	44.4%	41.6%	14.0%

Table 1.2: Percentage of Time Each of the PPBM Policies Achieved Lowest Long-term Cost, Under 243 Parameter Combinations and Both the Static and Dynamic Models

sets of circumstances favored which Bag-Match strategy. A straightforward approach would involve examining all possible combinations of our parameter estimates, which, because we have six parameters, would encompass $3^6 = 729$ possibilities. However, this direct approach would allow one set of scenarios with $B_5 = \$236$ million and $B_{100} = \$164$ million (i.e. in which 5% Bag-Match costs more than 100% Bag-Match). To avoid this absurdity, we make the assumption that the B_5 and B_{100} parameter estimates both take the same "status" (high, middle, or low value), which reduces our number of scenarios to $3^5 = 243$. (Note that, under the definitions of k_5 and γ_{100}, there is never any chance that 5% Bag-Match will be treated as more effective against terrorist attacks than 100% Bag-Match.)

1.7.2 Overall Analysis

We entered these 243 scenarios into an Excel spreadsheet, along with the PPBM policy dominance equations for the static and dynamic models. We then calculated which Bag-Match policy achieved the lowest long-term cost for each scenario, under both the static and dynamic models. In Table 1.2, we list the percentages of the scenarios for which each Bag-Match policy was optimal, under each model.

These percentages point to two trends: (1) 0% PPBM is optimal in a plurality of the scenarios under each model (a majority under one of them); and (2) 5% PPBM does substantially better, and 0% substantially worse, under the dynamic model than under the static model.

That 100% PPBM is optimal in an identical percentage of cases is not a surprise: we mentioned in Section 1.5.2, if 100% is optimal for a given scenario under the static model, so too will it be optimal for the dynamic model, and vice-versa. Examining the results of our calculations, we find that no scenario exists for which 5% PPBM is optimal under the static model, while 0% PPBM is optimal under the dynamic model. For 25.1% of the scenarios, 0% Bag-Match is optimal under the static model, while 5% Bag-Match is optimal under the dynamic model.

1.7.3 Specific Outcome Analysis

At this stage, we would like to examine the optimality results for various scenarios in order to illustrate which circumstances result in which PPBM strategy optimality outcomes. To facilitate this, let us introduce notation that will completely characterize a scenario. We have six parameters, but B_5 and B_{100} are linked, so each scenario can be characterized by a set of five letters, where each letter is either L, M, or H, corresponding to low, middle, or high parameter estimates. For example, we would interpret [L, M, H, L, H] as a scenario in which, in order, λ is at its low estimate, B_5 and B_{100} are at their middle estimates, $\tilde{C}$ is at its high estimate, k_5 is at its low estimate, and γ_{100} is at its high estimate.

100% Bag-Match Optimality

Let us first examine the 34 scenarios for which 100% Bag-Match is optimal under each model. These are listed in Table 1.3.

Scanning through these scenarios, we see that $\tilde{C}$ equals our high estimate in 32 of the 34 scenarios, while in the other two scenarios, it equals our middle estimate. In addition, λ must equal our middle or high estimate for 100% PPBM to be optimal. We also notice that γ_{100} never takes on the value corresponding to lowest further effectiveness beyond 5% Bag-Match. A simple calculation reveals that if incidents are extremely frequent and costly (i.e. high λ and $\tilde{C}$), 100% Bag-Match is optimal 2/3 of the time. If it is also true that 100% Bag-Match is highly effective (low γ_{100}), 100% PPBM is optimal 88.9% of the time. These results imply that having frequent and costly incidents, and an extremely effective 100% Bag-Match system, contribute substantially to the optimality of 100% Bag-Match.

Scenario Encoding:	[λ, B_5 and B_{100}, $\bar{C}$, k_5, γ_{100}]	
[M, L, H, L, L]	[M, M, H, L, L]	[M, H, H, L, L]
[M, L, H, M, L]	[M, M, H, M, L]	[M, H, H, M, L]
[M, L, H, M, M]	[M, M, H, M, M]	[M, H, H, M, M]
[M, L, H, H, L]	[M, M, H, H, L]	[M, H, H, H, L]
[M, L, H, H, M]	[M, M, H, H, M]	[H, L, H, L, L]
[H, M, H, L, L]	[H, H, H, L, L]	[H, L, H, L, M]
[H, M, H, L, M]	[H, H, H, L, M]	[H, L, M, M, L]
[H, L, H, M, L]	[H, M, H, M, L]	[H, H, H, M, L]
[H, L, H, M, M]	[H, M, H, M, M]	[H, H, H, M, M]
[H, L, M, H, L]	[H, L, H, H, L]	[H, M, H, H, L]
[H, H, H, H, L]	[H, L, H, H, M]	[H, M, H, H, M]
[H, H, H, H, M]		

Table 1.3: List of Scenarios in which 100% Bag-Match is Optimal for Both Models

If scenarios evidence all levels of estimates of a particular parameter, it will prove useful to consider a numeric measure of the "average" level for that parameter in a given scenario set. Let us pair the following integers with our estimate levels: "1" for a high estimate; "0" for a middle estimate; and "-1" for a low estimate. We define a parameter's "average" in a given scenario set to be the numerical average of the integers that correspond to the estimate levels that this parameter takes on in the scenario set. For instance, if in a set of six scenarios, λ equals the high estimate three times, the middle estimate twice, and the low estimate once, we would say that the "average" of λ for this scenario set is 1/3 (since $\frac{3(1)+2(0)+1(-1)}{6} = \frac{1}{3}$). Note that an average with a high (approaching 1) *absolute value* indicates a large degree of correlation between a parameter estimate level and a set of scenarios. Finally, we will use "AVG(x)" as shorthand for the average of parameter "x" for a given scenario set.

The set of scenarios in Table 1.3 evidences all levels of estimates for annual PPBM costs and 5% PPBM effectiveness, with the average of B_5/B_{100} equal to -0.09, and the average of k_5 equal to 0.09. These averages imply that the scenarios in this set include a few more cases with low annual PPBM costs than with high, and a few more cases with low [1] 5% PPBM effectiveness than with high. These results seems to

[1]High (Low) estimates for k_5 and γ_{100} correspond to 100% and 5% Bag-Match having low (high)

imply that annual PPBM costs and 5% PPBM effectiveness have less of an impact on 100% PPBM optimality than do incident-related costs, incident frequency, and the security added by 100% PPBM. In fact, even if annual PPBM costs are high, 100% PPBM is optimal for 2/3 of the cases if incident-related costs and incident frequency are also high. Likewise, if 5% is highly effective, 100% PPBM is optimal for 2/3 of the cases if incident-related costs and incident frequency are again, also high. We calculate the averages of λ, $\tilde{C}$, and γ_{100} to be 0.58, 0.94, and -0.58, respectively. Overall, then, we give the following order for degree of parameter correlation with 100% PPBM optimality, with the relevant parameter "average"in parenthesis: high incident-related costs (0.94), high risk of terrorism (0.58), high level of added security from 100% Bag-Match (-0.58), low 5% PPBM effectiveness (0.09), and low annual PPBM costs (-0.09). (Note that the average of any given parameter over the entire set of 243 scenarios is 0.)

5% Bag-Match Optimal Under the Dynamic and Static Models

Let us now examine the 40 scenarios for which 5% Bag-Match is optimal under both the static and dynamic models. We find these scenarios listed in Table 1.4.

In this set of scenarios, the "averages" for B_5/B_{100} and k_5 have the same value, -0.55. For $\tilde{C}$, γ_{100}, and λ, the averages are 0.525, 0.375, and 0.3, respectively. When annual PPBM costs are at our low estimate and 5% Bag-Match is extremely effective (low k_5), 5% Bag-Match is optimal under both the dynamic and static models 55.6% of the time. If it is also the case that incidents are very expensive (high $\tilde{C}$), 5% Bag-Match is optimal for both models 2/3 of the time. These parameter averages are consistent with what we might expect: in scenarios for which 5% PPBM is most cost-effective under both models, 5% PPBM tends to be more effective at preventing terrorist attacks, PPBM annual costs tend to be lower, and successful attack costs tend to be higher.

Comparing these results to the results for the scenarios from Table 1.3, we note

effectiveness. Therefore, positive averages for these two parameters give evidence of a tendency for lower PPBM effectiveness levels within a set of scenarios.

Encoding:	[λ, B_5 and B_{100}, $\tilde{C}$, k_5, γ_{100}]	
[L, L, H, L, L]	[L, L, H, L, M]	[L, L, H, L, H]
[L, L, H, M, L]	[L, L, H, M, M]	[L, L, H, M, H]
[M, L, M, L, L]	[M, L, M, L, M]	[M, L, H, L, M]
[M, M, H, L, M]	[M, H, H, L, M]	[M, L, M, L, H]
[M, L, H, L, H]	[M, M, H, L, H]	[M, H, H, L, H]
[M, L, M, M, L]	[M, L, M, M, M]	[M, L, M, M, H]
[M, L, H, M, H]	[M, M, H, M, H]	[M, H, H, M, H]
[M, L, H, H, H]	[H, L, L, L, L]	[H, L, M, L, L]
[H, M, M, L, L]	[H, L, L, L, M]	[H, L, M, L, M]
[H, M, H, L, M]	[H, L, L, L, H]	[H, L, M, L, H]
[H, L, H, L, H]	[H, M, M, L, H]	[H, M, H, L, H]
[H, H, H, L, H]	[H, L, M, M, M]	[H, L, M, M, H]
[H, L, H, M, H]	[H, M, H, M, H]	[H, H, H, M, H]
[H, L, H, H, H]		

Table 1.4: List of Scenarios in which 5% Bag-Match is Optimal for Both Models.

that the average of $\tilde{C}$ is much higher in the scenarios for which 100% PPBM was optimal under both models than its average is for this set of scenarios (0.94 as compared with 0.525). While 100% PPBM is very rarely optimal (2.5% of the time) when incident-related costs are at our low or middle estimate, 5% PPBM performs slightly better in those circumstances, as it is optimal 9.9% of the time. It might be that 5% PPBM performs better because there needs to be a larger cost savings from prevented terrorist attacks for 100% PPBM than 5% PPBM to justify the higher annual costs of 100% PPBM. We also note that the average for the PPBM annual cost parameter was more highly negative for this set of scenarios (-0.55) than it was for scenarios for which 100% PPBM was optimal under each model (-0.09). From this, it seems that 5% PPBM optimality is more sensitive to PPBM annual costs than is 100% PPBM optimality.

Examining the table, we note that it is almost always the case (38/40 scenarios) that 100% Bag-Match is not maximally effective. When 100% Bag-Match is maximally effective, it is almost never the case that 5% Bag-Match is the optimal strategy for both models, and this is presumably because an effective 100% Bag-Match policy provides a preferable alternative to 5% Bag-Match.

Overall, we have noted the following: in scenarios for which 5% PPBM is most

	Low Estimate	Middle Estimate	High Estimate
λ	41.7%	30.6%	27.8%
B_5&B_{100}	18.5%	39.8%	41.7%
$\tilde{C}$	41.7%	39.8%	18.5%
k_5	0.0%	38.0%	62.0%
γ_{100}	31.5%	33.3%	35.2%

Table 1.5: Parameter Estimate Percentages for the Scenarios in which 0% Bag-Match is Optimal for the Static and Dynamic Models

cost-effective under both models, (in order of decreasing absolute value of parameter average) 5% PPBM tends to be more effective (AVG(k_5) = -0.55), annual PPBM costs tend to be lower (AVG(B_5/B_{100}) = -0.55), incident-related costs tend to be higher (AVG($\tilde{C}$) = 0.525), 100% PPBM tends to offer less added security over 5% PPBM (AVG(γ_{100}) = 0.375), and successful attacks tend to be more frequent (AVG(λ) = 0.3).

0% PPBM Optimal for the Dynamic and Static Models

We next consider the set of scenarios for which no PPBM implementation at all is the most cost-effective strategy under both models, which represents 44.4% of the original scenario set. Listing all 108 scenarios from this set would be excessive, so we will instead make general observations regarding these scenarios, and mention a few illustrative cases. In Table 1.5, we list the percentage of these 108 scenarios for which each parameter took on the low, middle, and high estimates.

For this set of scenarios, the "averages" for k_5, B_5/B_{100}, and $\tilde{C}$ are 0.62, 0.23, and -0.23, respectively. For λ and γ_{100}, those averages are -0.14 and 0.04. We would expect the 0% Bag-Match strategy to be more competitive for low λ, high ongoing Bag-Match costs, low incident-related costs, and low effectiveness for the two Bag-Match implementations, and our averages are in line with these expectations.

k_5's average stands out the most, at 0.62, and implies that these scenarios tend to have low levels of 5% PPBM effectiveness. It makes sense that 0% Bag-Match's competitiveness is generally aided by 5% PPBM being less effective, but we notice from Table 1.5 that these scenarios do not include a single case of 5% PPBM being highly-effective. According to our analysis, if 5% PPBM is highly-effective, we should not expect 0% PPBM to be optimal under both models. When 5% Bag-Match is highly ineffective, 0% Bag-Match is optimal for both models 82.7% of the time.

Let us look in particular at two scenarios from this set: [L, M, H, M, L], and [M, M, M, M, M]. In this first case, incidents are infrequent, Bag-Match maintenance is moderately expensive, successful attacks prove extremely costly to the system, 5% PPBM is moderately effective, and 100% PPBM adds much security to 5% PPBM. Despite some parameter values that are quite favorable to PPBM, 0% Bag-Match is optimal under both models, in part due to the infrequency of incidents. For the static model, 0% PPBM is optimal 92.6% of the time when λ is at our low estimate. When we move to the dynamic model, if λ is at our low estimate, 0% PPBM is optimal 55.6% of the time. Particularly under the static model, there are few circumstances under which 0% Bag-Match is not optimal and incidents are very infrequent.

With the second listed scenario, we see that 0% PPBM is optimal under both models for the "perfectly average" scenario according to our parameter estimates. If we change this scenario so that 5% Bag-Match becomes highly effective, 0% Bag-Match is still optimal under the static model, but 5% becomes optimal under the dynamic model.

Overall, in scenarios from this set, 5% Bag-Match tends to add little security (AVG(k_5) = 0.62), Bag-Match annual costs tend to be high (AVG(B_5/B_{100}) = 0.23), incident-related costs tend to be lower (AVG($\tilde{C}$) = -0.23), and the terrorist risk tends to be lower (AVG(λ) = -0.14).

Optimal Policy Different Across Models

Finally, we consider the set of scenarios for which no PPBM implementation at all is the most cost-effective strategy under the static model, but 5% PPBM is optimal under the dynamic model. These 61 scenarios represent 25.1% of the original scenario set. In Table 1.6, we list the percentage of these scenarios for which each parameter took on the low, middle, and high estimates.

For this scenario set, we calculate the averages of k_5, $\tilde{C}$, and λ to be -0.79, -0.44,

	Low Estimate	Middle Estimate	High Estimate
λ	49.1%	29.5%	21.3%
$B_5\&B_{100}$	34.4%	31.1%	34.4%
$\tilde{C}$	54.1%	36.1%	9.8%
k_5	78.7%	21.3%	0.0%
γ_{100}	32.8%	32.8%	34.4%

Table 1.6: Parameter Estimate Percentages for the Scenarios in which 0% Wins for the Static Model, but 5% Wins for the Dynamic Model

and -0.28, respectively, while the averages of γ_{100} and B_5/B_{100} are just 0.02 and 0.00, respectively.

The importance of high 5% Bag-Match effectiveness (low k_5) in 5% Bag-Match's optimality under the dynamic model makes intuitive sense. Why the averages of $\tilde{C}$ and λ are negative is more difficult to understand. Indeed, *a priori* it is harder to imagine which parameter levels will bring about the case of 0% Bag-Match optimality under the static model but 5% Bag-Match optimality under the dynamic model (hereafter, the "split optimality" case). A high value in a given parameter might contribute to the optimality of 5% PPBM, but work against the optimality of 0% PPBM. Perhaps we do not see many scenarios here for which incidents are very frequent and costly because those characteristics would prevent 0% from being optimal in the static case, as they did in our analysis of the "no PPBM implementation wins under both models" case. When 5% Bag-Match is highly effective (low k_5) and "inexpensive" (low $\tilde{C}$), the split optimality case will occur 88.9% of the time. In these circumstances, it becomes all the more important to consider the static and dynamic assumptions, as the optimality of a PPBM policy is highly dependent on which assumption is made.

Let us look at the following scenario from the "split optimality" set: [M, L, L, M, H]. Here, 5% Bag-Match is moderately effective, while incidents are moderately frequent and relatively inexpensive. Annual Bag-Match costs are relatively low, and 100% Bag-Match is only marginally more effective than 5% Bag-Match. In the final paragraph of Section 1.4, we explained how the dynamic model introduces an implicit 0%/100% PPBM comparison into the 0%/5% PPBM comparison equation.

In order to understand why this occurs, remember the scenario given in that section: a successful terrorist attack occurs under 5% Bag-Match at time "t_5." It could well have occured earlier, at time "$t_0 = t_5 - x; x > 0$" had 0% Bag-Match been in operation, and if so, under the dynamic model, the FAA would require a switch to 100% Bag-Match at that earlier stage. From time t_5 to time $t_5 - x$, we would have 100% Bag-Match in operation had we started with 0% Bag-Match, and we would have 5% Bag-Match in operation had we started with 5% Bag-Match. For this reason, under the dynamic model we have an implicit 100%/5% Bag-Match comparison included in our comparison of 0% and 5% Bag-Match.

For the above scenario, [M, L, L, M, H], under the static model 100% Bag-Match is much less cost-effective (expected aggregate yearly cost, including incident-related costs, of $270 million) than either 5% Bag-Match ($176 million) or 0% Bag-Match ($140 million), while 5% Bag-Match is competitive with 0% Bag-Match. The inclusion of the implicit 0%/100% PPBM comparison into the dynamic model's 0%/5% PPBM comparison equation puts 0% PPBM at a disadvantage, due to the inferiority of 100% PPBM for this scenario; for this reason, 5% PPBM becomes the optimal policy as we move from the static to dynamic models. In general, for this static/dynamic model "inconsistency" to occur, 100% PPBM must be dominated by 5% PPBM under the static model. From 5% PPBM's substantial improvement under the dynamic model, we would expect 5% PPBM to have beaten 100% PPBM quite often under the static model. Otherwise, 5% PPBM would not make up much ground on 0% PPBM as we move to the dynamic model. Indeed, under the static model, 100% Bag-Match is dominated by 5% Bag-Match in 82.3% of the scenarios, which does much to explain 5% Bag-Match's improvement under the dynamic model.

For scenarios from this set, 5% Bag-Match tends to be more effective ($\text{AVG}(k_5) = -0.79$), incident-related costs tend to be lower ($\text{AVG}(\tilde{C}) = -0.44$), and the terrorist risk tends to be lower ($\text{AVG}(\lambda) = -0.28$).

Results Summary

In this section, we have examined the overall performance of each of the three Bag-Match policies under the static and dynamic models. We have observed relationships that make intuitive sense: the partial and full Bag-Match implementations are often favored when incidents are frequent and costly, and when Bag-Match is effective. However, it was not obvious, *a priori*, which policies would be optimal under each model for a given scenario without computations based on these models. For 100% Bag-Match to be optimal, we found that it is all but necessary that incident costs be extremely high - in only two scenarios was 100% Bag-Match optimal without this being true. When 0% PPBM was optimal under both models, for no scenario was it also true that 5% PPBM was highly effective. However, when 0% Bag-Match was optimal for the static model and 5% Bag-Match was optimal for the dynamic model, it was very often the case that 5% Bag-Match was highly effective. As for overall performance, the 0% PPBM strategy was optimal for a sizeable portion of the scenarios when we assumed that there would be no PPBM policy switch in the wake of a successful attack. When we assumed a policy switch to 100% PPBM, 0% and 5% Bag-Match were optimal in a comparable number of scenarios. Under both assumptions, 100% Bag-Match was optimal in just a seventh of the scenarios.

1.8 Caveats

In this thesis, we are working with approximate models and imprecise estimates about the parameters of these models. We based our estimates of λ on the historical rate of successful terrorist attacks via checked luggage on US domestic aviation and on civil aviation outside of the US domestic sphere. First, the degree to which the future will resemble the past, with regard to λ, is unknown. For example, future US foreign policy actions might lead to an increase or decrease in the magnitude of the terrorist threat to US domestic aviation. Or perhaps terrorists will obtain or develop less-detectable explosive devices, making an attack on civil aviation a more attractive option to them. Second, it is plausible that the rate of future successful terrorist attacks via checked luggage is substantially different for US domestic flights than it is for international or foreign domestic flights, yet we used the historical rate of terrorist attacks on flights that are *not US domestic* as the basis for one of our estimates for λ Thus, it would be misleading to claim a high degree of accuracy surrounding our estimate of λ.

We have also assumed that successful terrorist attacks occur according to a fixed-parameter Poisson Process, which, in turn, assumes that the probability of an event occuring in a given time interval is independent of what happens in prior intervals. If, however, a successful terrorist attack were to encourage other attacks of the same sort, this independence assumption would be violated. Furthermore, our model assumes that the average annual risk of these terrorist attacks via checked baggage is fixed, while, as we have mentioned, this risk might very well change over time. We do note that one of the strengths of this analysis is that it suggests how the optimal PPBM strategy should vary with the underlying degree of threat.

In estimating the dollar costs associated with deaths in luggage bombings, $\tilde{C}$, we worked from the estimated cost of lawsuits and settlements for a single flight, Pan Am 103. We were not able to locate figures on the total lawsuit-related costs for the incident, and there was a scarcity of similar incidents for which such figures are readily available, so we used what was available in making our estimates.

To estimate the loss of passenger revenue that would result from an incident, we considered various successful attack scenarios, and assigned what we thought were plausible values for the percentage of 1997 annual US carrier domestic revenue that might be lost in these scenarios. These percentages were not based on a systematic study or on historical data, so their accuracy is more suspect than that of some of the other parameters we estimated. If it had been the case that revenue loss from terrorist attacks was readily estimated, or if accurate figures of this loss were available, we would not have relied as much on "percentage of annual revenue loss" estimates.

More generally, it is difficult to predict what the fatality levels in successful, future luggage-bomb attacks might be, and the extent to which such attacks will frighten people away from air travel. If we consider the aforementioned 1995 Ramzi Ahmed

Yousef plot to place bombs on twelve US passenger airliners, we might imagine that, had his plot been even partially successful, the costs would have far exceeded our high estimate for $\tilde{C}$.

We based our estimates of the annual costs of implementing a PPBM policy on the results from [4], but, as the authors themselves mention, their cost estimates have the following limitations:

(1) The PPBM Live-Test involved just 4% of flights, rather than a system-wide implementation, and inefficiencies that might be present at the outset of PPBM operation might not persist with the same severity in the long-term. Due to circumstances such as these, Barnett et al. were forced to extrapolate what the effects from a long-term, system-wide PPBM implementation might be.

(2) The air carriers decided to suspend the Live Test when severe weather problems disrupted operations, so as not to aggravate already difficult situations.

(3) Barnett et al. projected the ongoing costs of 5% PPBM via reverse-engineering of the 100% PPBM results, and, as they mentioned, "it is unclear how much easier and cheaper it is to focus on a small minority of passengers rather than all."

Each of these statements points to a source of inaccuracy in NEXTOR's estimates for the yearly annual PPBM costs. However, as these estimates are the results of a thorough experiment which involved an actual implementation of PPBM, we have much more confidence in their accuracy than we do in that of our estimates of, say, $\tilde{C}$.

We also made estimates for the probabilities that 5% and 100% Bag-Match will prevent a terrorist attack. These estimates are highly speculative, by nature, as we are estimating the likelihood that a PPBM strategy will forestall a future terrorist attack. To reflect this uncertainty, we gave widely-ranging estimates for these parameters: we allowed k_5 to range from 0.25 to 0.875, and γ_{100} to range from 0.125 to 0.875. The spreads of these estimates allow us to consider possibilities ranging from near-uselessness to high effectiveness for the two PPBM policies, and we feel that it is unlikely that k_5 and γ_{100} values outside of these ranges would be possible. We concede that a tighter, but more accurate, range might be preferable, but we were not able to provide such a range with much confidence.

Finally, we ask ourselves the question: "Is long-term expected cost the appropriate criterion for choosing a Bag-Match strategy?" Long-term expected cost is of obvious import to the US carriers which would have the responsibility of implementing a Bag-Match policy and would suffer the financial consequences of terrorist attacks. US carriers will have more interest in, and perhaps push for, implementing a safety policy that they see as financially viable or even money-saving. The FAA, like any policy-setting body, must be concerned with the extent and nature of the effects a policy change might have, as well as with the constituents that will be affected. For these reasons, the long-term expected cost of a PPBM policy decision is of interest to both the FAA and the US airlines. However, this cost is just one measure, albeit important, of the impact a policy will have on the aviation system. One might argue for the inclusion of measures that are more difficult to quantify, such as "passenger peace of mind," as an additional criterion. Passengers might very well be willing to pay a small ticket surcharge to reduce the risk of successful terrorist acts, even if that risk is quite small. This possibility is not considered in the cost-effectiveness model.

We concede that our analysis of PPBM has been based on a single criterion, long-term expected cost, that might exclude other important considerations, but we maintain that this criterion is of great interest to both the FAA and the US carriers. We would encourage attempts at examining other consequences of PPBM policy changes, such as an increase in "passenger peace of mind," that we did not cover in this thesis.

The imperfections of this analysis compromise its results to an unknown extent. That said, this study does provide a comparison of the long-term expected costs that various PPBM strategies might involve, under a variety of assumptions. More specifically, it gives some indication of the kinds of assumptions one has to make to proclaim a particular policy superior to alternatives. In addition, our analysis gives the reader the option of undertaking her own analysis of these issues, based on different parameter estimates. Despite its imperfections, our work does provide a quantitative analysis of a pressing civil aviation policy issue, the implementation of

PPBM, where there had been limited prior research.

1.9 Summary and Conclusions

In this thesis, we have worked on an optimization problem that was implicitly posed by the FAA: "Under which conditions are each of no Bag-Match (hereafter, 0% PPB-M), 5% Bag-Match with passenger profiling, and 100% Bag-Match, optimal for US domestic flights?" The FAA expressed a strong preference for 5% Bag-Match, but we decided to approach this optimality question ourselves, from an analytic perspective.

We used probabilistic modeling to describe the process by which successful terrorist attacks, via checked luggage, might occur on US domestic flights. We reasoned that, in the wake of a successful attack, the FAA could either recommend a switch to full PPBM implementation or leave in place the PPBM policy that had been in operation at the time of the attack. We developed models for each possibility, and derived equations in order to compare the long-term expected cost of the three Bag-Match options: no implementation of PPBM, 5% PPBM with passenger profiling, and 100% PPBM. Using highly approximate methods, we arrived at low, middle, and high estimates for each of the models' parameters. To do so, we considered how often we might expect successful terrorist attacks in the future, absent PPBM, and also how much success 5% and 100% PPBM would have in preventing these attacks. We also considered how expensive 5% and 100% PPBM might be to implement, and how expensive successful terrorist attacks would be. We enumerated what we considered a set of plausible scenarios, and examined the performance of the three PPBM policies over the full set of cases, both under the assumption that, after an incident, the FAA would recommend a switch to 100% PPBM (the "dynamic" assumption) and under the assumption that it would leave the previous PPBM policy in place (the "static" assumption).

Under the "static" assumption, our assessment indicated that the policy of not implementing PPBM at all was most "cost-effective" (i.e. optimal) for a greater proportion of the scenarios than was either of the two Bag-Match alternatives. In particular, we found that not implementing Bag-Match at all would be the optimal decision under the static model in 69.5% of the scenarios, 5% Bag-Match would be optimal in 16.5% of the scenarios, and 100% Bag-Match, in 14.0% of the cases. From these results, one might conclude that if the "static" assumption holds true, money might be better spent on other hazards to air travelers than on a partial or full Bag-Match implementation.

Under the "dynamic" assumption, our analysis indicated that 0% PPBM was most cost-effective in 44.4% of the scenarios, that 5% PPBM was the most cost-effective in 41.6% of the scenarios, and that 100% PPBM was again the optimal policy in just 14.0% of the cases. We noted the substantial improvement in performance of 5% Bag-Match under this assumption, looked at a scenario under which 5% Bag-Match became optimal as we moved from the static to the dynamic assumption, and gave reasons for this improvement. From these results, if the dynamic assumption proves to be realistic, policy makers might be best off recommending either no PPBM implementation at all, or a 5% PPBM implementation.

Under each assumption, a full-implementation of PPBM does "win" under a limited set of circumstances: in general, when 100% PPBM provides much added security over 5% PPBM, and when terrorist attacks are frequent and highly costly. 5% PPBM is optimal under each assumption in a majority of cases in which annual PPBM costs are low, 5% Bag-Match is highly effective, and incident-related costs are high. These sets of circumstances comprise a substantial portion of the scenario set, and it very well might be the case that a "100% PPBM-friendly" or "5% PPBM-friendly" scenario most accurately represents the present and future reality. To dismiss either 100% or 5% Bag-Match as an inferior policy due to these results would be foolish.

We stress that our analysis has its limitations, but that our results suggest that the FAA-recommended 5% PPBM policy is not necessarily too lax or too stringent. Each of the three levels of Bag-Match implementation (or non-implementation, as the case may be) was optimal for a substantial subset of the scenarios we considered. As we have seen, the optimality of a Bag-Match policy depends on the magnitude of the terrorist threat and the effectiveness of Bag-Match in counteracting it. Any improvements in assessing these factors would allow for more accurate modeling and more reliable decision-making.

Appendix A

Relevant Acts of Terrorism

Successful Acts of Terrorist Agression via Checked Luggage from 1950 to 1999

1955, November 1. United Air Lines flight #629 [1], from Denver to Seattle. 44/44 dead. "11 minutes after takeoff an explosion disintegrated the aircraft in flight. A dynamite bomb detonated in No. 4 *baggage* compartment. 39 Passengers; 5 crew. J. Graham executed for the crime." [9]

1972, January 26. Jugoslovenski Aero-transport (Yugoslavia) flight #364, over Ceske Kamenice, Czechoslovakia. 27/28 dead. "Homemade bomb in forward *luggage compartment.* Aircraft crashed; 28 persons aboard. (Note: Sole survivor fell approximately 15,000 feet in tail section.)" [9]

1976, January 1. Middle East Airlines (Lebanon) flight #438, between Saudi Arabia and Kuwait. 82/82 dead. "The jetliner crashed into the Arabian desert after an explosion aboard the aircraft caused a high order explosion in *forward baggage compartment.*" [9]

1981, August 31. Middle East Airlines (Lebanon), on the ground at Beirut. 2 killed.[5] "Explosion estimated at 5 kilograms of dynamite severely damaged the empty aircraft. Explosion occurred shortly after the aircraft completed a flight from Libya." [9]

[1] Flight numbers were taken from [5] in most cases

1983, September 23. Gulf Air (Bahrain) flight #771, 30 miles from Abu Dhabi, United Arab Emirates. 112/112 dead. "Bomb exploded *in the baggage compartment.* The aircraft crashed in the desert while preparing to land." [9]

1985, June 23. Air India flight #182, about 90 miles off the coast of Ireland. 329/329 dead. "As the aircraft neared Ireland, it disappeared from the radar screen and crashed in the ocean. After examining the wreckage, scientists reported [sic] a powerful explosion occurred in the *front cargo hold.*" [9] "Terrorist working in Vancouver, Canada, checked baggage with bombs on two flights. One bag transferred at Toronto onto flight 182." [5]

1988, December 21. Pan Am flight #103, over Lockerbie, Scotland. 259/259 passengers dead. 11 killed on ground. "The airliner disappeared from radar shortly after leveling off at FL 310 while on a flight from Heathrow Airport, London, to New York ... Detonation of an explosive device in the forward cargo area." [5] "Located in baggage compartment." [9]

1989, September 19. Union des Transportes Aeriens (France) flight #772, near Niger. 171/171 dead. "While climbing through FL 350 ft., 46 minutes after takeoff, a bomb exploded in a container in location 13-R in the forward cargo hold ... A Congolese man, who boarded at Brazzaville and disembarked at Ndjamera was believed to have brought the bomb aboard." [5]

References

[1] Federal Aviation Administration. *Report to Congress on the Domestic Baggage Match Program*, 1998.

[2] Federal Aviation Administration. Security of Checked Baggage on Flights Within the United States. Docket No. FAA-1999-5536; Notice No. 99-05, 1999.

[3] Barnett A.I. A Parallel Approach Path to Estimating Collision Risk During Simultaneous Landing. *Management Science* 45, 382-394, 1999.

[4] Barnett A.I., R. Shumsky, M. Hansen, A. Odoni, and G. Goslingle. Safe at home? an experiment in domestic airline security. *Operations Research*, Forthcoming.

[5] PlaneCrashInfo.com. Aviation Accident Database. www.planecrashinfo.com, Consulted in 2000.

[6] The World Wide Legal Information Association Web Site. Some Recent FBI Investigations. URL: www.wwlia.org/us-fbi.htm#recent, Consulted in 2000.

[7] State Department Office of the Coordinator for Counterterrorism. *Report to Congress.* Patterns of Global Terrorism, 1996.

[8] White House Commission on Aviation Safety and Chairman Security. Vice President Al Gore. Final Report to President Clinton, 1997.

[9] President's Commission on Aviation Security and Terrorism. *Report to the President.* Appendix E: Acts of Aviation Sabotage, 1990.

[10] Air Transport Association Web Site. FAA Aviation Forecasts. URL: www.air-transport.org/public/industry/48.asp, Consulted in 2000.

[11] Air Transport Association Web Site. Industry Information. URL: www.air-transport.org/public/industry/45.asp, Consulted in 2000.

[12] Air Transport Association Web Site. Traffic and Operations Data. URL: www.air-transport.org/public/industry/43.asp, Consulted in 2000.

[13] Boeing Web Site. Commercial Airplanes. 2000 Airplane Prices. URL: www.boeing.com/commercial/prices/index.html, Consulted in 2000.

[14] United Kingdom Air Accidents Investigation Branch Web Site. Aircraft Accident Report No 2/90 (EW/C1094). URL: www.open.gov.uk/aaib/n739pa.htm#Injuries, Consulted in 2000.

[15] Associated Press via Pan Am 103/Lockerbie Crash Web Site. The Victims of Pan Am 103. URL: www.geocities.com/CapitolHill/5260/victim.html#pay, Consulted in 2000.