Dynamic, Risk-Based Aviation Security Screening Policy Performance Analysis Using Simulation

Sheldon H. Jacobson
Department of Computer Science
University of Illinois at Urbana-Champaign

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Ni Hao

Ni hui shuo yingyu ma?

I hope so!
Research Motivation

- Investigate passenger / baggage screening operations
- Effectively utilize security resources
- Maximize security system effectiveness
- Design security systems that work!
Overview

• Introduction
• Historical Background
• Steady State Assignment Policy
  – Maximize passenger throughput
• Transient Assignment Policy
  – Maximize security and passenger throughput
• Selective Screening Systems
• Simulation Results
• Observations and Conclusions
Introduction

• Aviation Security: A New Era
  – September 11, 2001
    • Terrorist attacks on World Trade Center Twin Towers and Pentagon
  – Ongoing Events
    • August 10, 2006: Plot to destroy ten U.S. bound transatlantic flights
    • December 25, 2009: Christmas day bomber
    • May 7, 2012: Al-Qaeda bomber

• Transportation Security Administration (TSA)

• Changes to aviation security systems
  – Reinforced cockpit doors
  – Expanded federal air marshal program
  – Behavior detection techniques (SPOT)
  – 100% checked baggage screening
  – 3-1-1 liquid and gel policy
  – Advanced Imaging Technologies
Passenger Screening Techniques

Uniform screening

• Rationale: All passengers could pose a threat
• Passenger risk perceived equally
• Used from 1970’s to 1998

Selective screening

• Rationale: Majority of passengers pose no threat
• Select passengers perceived as higher risk
• Targets expensive, specialized resources at high-risk passengers
• Used from 1998 to 2001
• TSA Pre✓ is the new trusted traveler program
Passenger Prescreening Programs

- **Computer-Assisted Passenger Prescreening System (CAPPS)**
  - *Selectees* - those not cleared by CAPPS
  - *Nonselectees* - those cleared by CAPPS
  - **CAPPS II (2003)**
    - Lacked proper analysis and tests during development
    - Dismantled due to privacy concerns

- **Secure Flight (2004)**

- **Registered Traveler (RT) programs**
  - Expedites screening process for RT members (Global Entry, Nexus)
  - **TSA Pre✓**
Baggage and Cargo Screening

• Commission on Aviation Safety and Security, July 1996
  – Explosive detection systems (EDSs)
  – Automated passenger prescreening (i.e., CAPPS)
  – Positive passenger-baggage matching (PPBM)

• Aviation and Transportation Security Act (ATSA)
  – 100% screening of checked baggage by December 31, 2002

• 9/11 Commission Act of 2007 – Recommendations
  – Required “screening” of
    • 50% of cargo on passenger aircraft by February 2009
    • 100% of cargo by August 2010
  – Security Programs
    • Explosives detection canine teams
    • Transportation Security Inspectors (TSIs) for cargo
Current Passenger Screening Programs

• Checkpoint Evolution
  – People
    • Travel Document Checker (TDC)
    • Visible Intermodal Prevention and Response (VIPR)
    • Screening Passengers by Observation Technique (SPOT)
    • Chat downs
  – Process
    • Diamond Self-Select program (3 groups)
    • TSA Pre✓
  – Technology
    • Advanced Imaging Technology (AIT)
    • Trace Devices
    • Bottle Liquid Scanners (BLS)
Definitions

• A **threat** is a passenger or item that may be involved in the attack of an aircraft or within the airport terminal

• A **device** is a technology or procedure used to detect a threat

• The device **capacity** is an upper bound on the number of passengers or bags that a device can screen

• A **security class** is a subset of devices and procedures through which a passenger may be screened

• **Multi-level screening** is an aviation security system in which there exists several security classes to screen passengers

• An **assessed threat value** quantifies the passenger’s perceived risk level through an automated prescreening system
Device Alarm Responses (EPIC)

• **True Alarm** (Effective)
  – An alarm occurs for a passenger/bag containing a threat item
  – Correctly identifies a potential terrorist attack

• **False Clear** (Perilous)
  – No alarm occurs for a passenger/bag containing a threat item
  – Incorrectly allows a potential terrorist to enter the airport terminal

• **False Alarm** (Inefficient)
  – An alarm occurs for a passenger/bag containing no threat items
  – Requires additional screening, cost, time

• **True Clear** (Convenient)
  – No alarm occurs for a passenger/bag containing no threat items
  – Correctly clears nonthreatening passenger
Designing Effective Screening Systems

• Challenges
  – Budget limitations, time consuming, questionable effectiveness

• Improving security screening systems
  – Screen high-risk subjects with expensive, low throughput devices
  – Design *layered* approach to screening passengers, baggage and cargo
  – Assign passengers, baggage, cargo based on *perceived risk*

• Modeling Approach
  – *Real-time dynamic model*
  – Maximize security, subject to device constraints
Motivation

Objectives

- Maximize security (overall true alarm rate)
- Minimize expected time passenger spends in security system

- Queueing aspects of passenger screening process
- Continual arrival of passengers at security checkpoint \((N \to +\infty)\)
- Multi-level vs. selective screening systems
Setting and Notation

- Queue capacity $c_m$ for security class $m = 1, 2, \ldots, M$
- Assessed threat value $\alpha_i$ of passenger $i$
  - Quantifies perceived risk resulting from prescreening
- Conditional probability of security class $m$ detecting threat, $L_m$ (i.e., device true alarm rate)
Setting and Notation

• **Passenger arrivals**
  – Independent
  – Poisson process with rate $\lambda > 0$
  – $t_i =$ time passenger $i$ arrives at security checkpoint ($t_i \to \infty$ as $i \to \infty$)

• **Security class service times**
  – Exponential, with rates $\mu_1 > \mu_2 > \ldots \mu_M > 0$
  – Stability
    \[\lambda < \sum_{m=1}^{M} \mu_m\]

• **Passenger assignments**
  – Probability passenger $i$ assigned to security class $m$
    \[p_m(t_i) \equiv P(X_m(t_i) = 1)\]
Multi-level Security Class System

- $c_m$: Queue capacity for security class $m = 1, 2, \ldots, M$
- Security classes operate independently
Steady State Assignment Policy

- Passenger assignments made independently
- Predetermined set of fixed security class threshold values
- Each security class has infinite capacity \( (c_m = +\infty, m = 1, 2, \ldots, M) \)
- Discrete random variables
  - \( N^a(t) \): Number of passengers that arrive for screening by time \( t \)
  - \( N^a_m(t) \): Number of passengers assigned to class \( m \) by time \( t \)
    \[ N^a(t) = \sum_{m=1}^{M} N^a_m(t) \]
  - \( N^d_m(t) \): Number of passengers screened in class \( m \) by time \( t \)
  - \( S_m(t) \): Number of passengers in security class \( m \) at time \( t \)
    \[ S_m(t) = N^a_m(t) - N^d_m(t) \]
One-Step Analysis

• \{N_m^a(t), \ t \geq 0\}, \ m = 1,2,...,M \text{ independent Poisson processes, with rate } \lambda p_m, \text{ where } p_m \equiv P(X_m(t_i) = 1)

• Probability transition rates (Chapman Kolmogorov Equations)

\[
\frac{d}{dt} P(S_m(t) = 0) = -\lambda p_m P(S_m(t) = 0) + \mu_m P(S_m(t) = 1)
\]

\[
\frac{d}{dt} P(S_m(t) = s_m) = -\lambda p_m (P(S_m(t) = s_m) - P(S_m(t) = s_m - 1))
\]

\[
+ \mu_m (P(S_m(t) = s_m + 1) - P(S_m(t) = s_m)), \quad s_m \geq 1
\]

• Steady-state probabilities

\[P_s^m \equiv \lim_{t \to \infty} P(S_m(t) = s) = P(S_m = s)\]

• Geometric distribution

\[P_s^m = \left(1 - \frac{\lambda p_m}{\mu_m}\right)\left(\frac{\lambda p_m}{\mu_m}\right)^s, \quad \lambda p_m < \mu_m\]
Expectation and Variance

- Standard Queueing Results for Security Class $m = 1, 2, \ldots, M$
  
  - $S_m = \text{Steady-state number of passengers in security class } m$
    
    $$E[S_m] = \frac{\lambda p_m}{\mu_m - \lambda p_m}, \quad \text{Var}(S_m) = \frac{\mu_m \lambda p_m}{(\mu_m - \lambda p_m)^2} \quad \lambda_m < \mu_m$$

  - $W_m = \text{Steady-state amount of time a passenger spends in class } m$
    
    $$E[W_m] = \frac{1}{\mu_m - \lambda p_m}, \quad \text{Var}(W_m) = \frac{\mu_m}{\lambda p_m (\mu_m - \lambda p_m)^2} \quad \lambda_m < \mu_m, \ p_m \neq 0$$

- Security system
  
  $$E[S] = \sum_{m=1}^{M} E[S_m] \quad \text{Var}(S) = \sum_{m=1}^{M} \text{Var}(S_m)$$

  $$E[W] = \sum_{m=1}^{M} p_m E[W_m] \quad \text{Var}(W) = \sum_{m=1}^{M} p_m^2 \text{Var}(W_m)$$

- Service rate mean, variance:
  
  $$\bar{\mu} = \frac{1}{M} \sum_{m=1}^{M} \mu_m, \quad \sigma_{\mu}^2 = \frac{1}{M} \sum_{m=1}^{M} (\mu_m - \bar{\mu})^2$$
Steady State Solutions

• Equalize $E[S_m]$ across $m = 1,2,...,M$ \implies \boxed{p_m = \frac{\mu_m}{M\bar{\mu}}}

\[E[S] = \frac{M\lambda}{M\bar{\mu} - \lambda} \quad Var(S) = \frac{M^2\bar{\mu}\lambda}{(M\bar{\mu} - \lambda)^2}\]

\[E[W] = \frac{M}{M\bar{\mu} - \lambda} \quad Var(W) = \frac{M^2\bar{\mu}}{\lambda(M\bar{\mu} - \lambda)^2}\]

• Equalize $E[W_m]$ across $m = 1,2,...,M$ \implies \boxed{p_m = \frac{1}{\lambda}(\mu_m - \bar{\mu}) + \frac{1}{M}}

\[E[S] = \frac{M\lambda}{M\bar{\mu} - \lambda} \quad Var(S) = \left(\frac{M}{M\bar{\mu} - \lambda}\right)^2 \left(M\sigma^2_\mu + \lambda\bar{\mu}\right)\]

\[E[W] = \frac{M}{M\bar{\mu} - \lambda} \quad Var(W) = \left(\frac{M}{\lambda(M\bar{\mu} - \lambda)}\right)^2 \left(M\sigma^2_\mu + \lambda\bar{\mu}\right)\]
Static Passenger Queueing Problem (SPQP)

- Minimize expected passenger security sojourn time, $E[W]$

\[
\begin{align*}
\min & \quad \sum_{m=1}^{M} \frac{p_m}{\mu_m - \lambda p_m} \\
\text{subject to} & \quad 0 \leq p_m \leq 1 \quad m = 1, 2, \ldots, M \\
& \quad p_m < \frac{\mu_m}{\lambda} \quad m = 1, 2, \ldots, M \\
& \quad \sum_{m=1}^{M} p_m = 1
\end{align*}
\]

- Solve nonlinear program (NLP) for $p_1, p_2, \ldots, p_M$

- Second inequality constraint replaced with $p_m + \varepsilon_m \leq \frac{\mu_m}{\lambda}$
  - Take limit as $\varepsilon_m \to 0$
Example: Two-Class Security System

- \( p_1 = P(X_1(t_i)=1), \ p_2 = P(X_2(t_i)=1) = 1 - p_1, \) with \( \mu_1 + \mu_2 > \lambda, \mu_1 > \mu_2 \)
- Solution to SPQP

\[
p_1^* = \frac{\mu_1(\lambda - 2\mu_2)}{\lambda(\mu_1 - \mu_2)} + \sqrt{\left(\frac{\mu_1(\lambda - 2\mu_2)}{\lambda(\mu_1 - \mu_2)}\right)^2 + \frac{\mu_1\mu_2}{\lambda^2} - \frac{\mu_1(\lambda - 2\mu_2)}{\lambda(\mu_1 - \mu_2)}}
\]

\[
p_2^* = \frac{\mu_2(2\mu_1 - \lambda)}{\lambda(\mu_1 - \mu_2)} - \sqrt{\left(\frac{\mu_1(\lambda - 2\mu_2)}{\lambda(\mu_1 - \mu_2)}\right)^2 + \frac{\mu_1\mu_2}{\lambda^2} - \frac{\mu_1(\lambda - 2\mu_2)}{\lambda(\mu_1 - \mu_2)}}
\]

- If \( \mu_1 = \mu_2, \) then \( p_1^* = p_2^* = 1/2 \)
Transient Assignment Policy

• Objectives
  – **Maximize** security (true alarm rate)
  – **Minimize** expected passenger security sojourn time

• Queueing analysis
  – Observe the screening process at each passenger arrival time
  – Interarrival times: exponential with rate $\lambda > 0$
    • $\delta_i = t_i - t_{i-1}$
  – **Finite** security class capacities, $c_m$

• Weighted cost function
  – Minimize cost to create balance between objectives
Transient Analysis

• Number of passengers screened in class $m$ during $(t_i, t_{i+1}]$

$$N^s_m(t_i, t_{i+1}) = N^d_m(t_{i+1}) - N^d_m(t_i)$$

  – Independent of passenger arrival time, $t_i$
  – Dependent on number of passengers in the system at time $t_i$, $\{S_m(t_i)\}$

• Conditional probability for the number of passengers screened

$$P(N^s_m(t_i, t_{i+1}) = n^s_m|S_m(t_i) = s_m) = \begin{cases} 
  e^{-\mu_m\delta_{i+1}} (\mu_m \delta_{i+1})^{n^s_m} / n^s_m! & \text{if } n^s_m < s_m \\
  1 - \sum_{n^s_m=0}^{s_m-1} e^{-\mu_m\delta_{i+1}} (\mu_m \delta_{i+1})^{n^s_m} / n^s_m! & \text{if } n^s_m = s_m \\
  1 & \text{if } s_m = 0 
\end{cases}$$
Markov Chain

- Model as discrete-time, inhomogeneous Markov chain

\[
P_m^{k,i}(t_i) = \begin{cases} 
(1-p_m(t_i))P(N_{m}^s(t_i,t_{i+1}) = k|S_m(t_i) = k) \\
+ p_m(t_i)P(N_{m}^s(t_i,t_{i+1}) = k+1|S_m(t_i) = k) \\
p_m(t_i)P(N_{m}^s(t_i,t_{i+1}) = 0|S_m(t_i) = k) \\
(1-p_m(t_i))P(N_{m}^s(t_i,t_{i+1}) = k-j|S_m(t_i) = k) \\
+ p_m(t_i)P(N_{m}^s(t_i,t_{i+1}) = k-j+1|S_m(t_i) = k) \\
P(N_{m}^s(t_i,t_{i+1}) = 0|S_m(t_i) = k) \\
0 \end{cases} 
\]

- Boundary condition

\[
P(S_m(t_1) = s_m) = \begin{cases} 
1 & \text{if } s_m = 0 \\
0 & \text{otherwise} 
\end{cases}
\]

- States \( s_m = 0,1,...,c_m \) positive recurrent and aperiodic
Closed-Form Recursions

• Expected number of passengers in security class $m$

\[ E[S_m(t_{i+1})] = E[S_m(t_i)] + p_m(t_i) \left[ 1 - P(N^s_m(t_i, t_{i+1}) = 0, S_m(t_i) = c_m) \right] - E[N^s_m(t_i, t_{i+1})] \]

  - Boundary condition, $E[S_m(t_1)] = 0$

• Expected amount of time passenger $i+1$ spends in security system if assigned to security class $m$

\[ E[W_m(t_{i+1})] = E[W_m(t_i)] + \frac{p_m(t_i)}{\mu_m} \left[ 1 - P(N^s_m(t_i, t_{i+1}) = 0, S_m(t_i) = c_m) \right] - \frac{1}{\mu_m} E[N^s_m(t_i, t_{i+1})] \]

  - Boundary condition, $E[W_m(t_1)] = 1/\mu_m$

• Security class threshold values

\[ b_m(t_i) = F^{-1}_\alpha \left( \sum_{j=1}^{m} p_j(t_i) \right) \]
Cost Function Components

• False Clears

\[ C_Z(t_i) = \left( 1 - \sum_{m=1}^{M} \frac{L_m - L_1}{L_M - L_1} p_m(t_i) \right)^2 \]

• Passenger Sojourn Times

\[ C_W(t_i) = \left( \frac{\sum_{m=1}^{M} p_m(t_i) E[W_m(t_i)] - \omega^*}{\max_{m=1,2,...,M} \{E[W_m(t_i)]\} - \omega^*} \right)^2 \]

  – Optimal, steady-state expected amount of time a passenger spends in the security system, \( \omega^* = \sum_{m=1,2,...,M} p_m^* \omega_m^* \)

• Optimal assignment probability error, \( p_m(t_i) - p_m^* \)

\[ C_P(t_i) = \frac{1}{M-1} \sum_{m=1}^{M-1} \left( 1 - \frac{p_m(t_i)}{p^*} \right)^2 \text{ where } p^* = \max\{p_m^*\} \]
Dynamic Passenger Queueing Problem

• Total Weighted Cost Function
  
  $0 \leq \eta_1 \leq 1$, $0 \leq \eta_2 \leq 1$

  minimize \quad $C(t_i) = (1 - \eta_1)C^z(t_i) + \eta_1((1 - \eta_2)C^w(t_i) + \eta_2 C^p(t_i))$

  subject to \quad $0 \leq p_m(t_i) \leq 1$, \quad $m = 1, 2, ..., M$

  $\sum_{m=1}^{M} p_m(t_i) = 1$

• Solve nonlinear program for $p_1(t_i), p_2(t_i), ..., p_M(t_i)$
Simulation Model

Used to compare security screening policies and conduct sensitivity analysis on the objective function parameters.

Threshold values (used to assigned passengers to classes) are updated each time a passenger arrives, by solving the NLP for the SPQP.

\[ b_m(t_i) = F_{\alpha}^{-1} \left( \sum_{j=1}^{m} p_j(t_i) \right) \]

Independently seeded runs are used to estimate the mean and the variance of the number of threat items detected and of the time spent within the screening process.
Selective Screening

- Optimal assignment probability for secondary screening
  - Nonselectees
    \[
    p^*(t_i) = \begin{cases} 
      \frac{1 - \eta_1}{1 - p_s} & \text{if } S_2(t_i) < c_2 \\
      0 & \text{otherwise}
    \end{cases}
    \]
  - Selectees, \( p^*(t_i) = 1 \)
  - \( p_s \) = fraction of passengers designated as selectees
Simulation Results

- $M = 2$ class security system, with $N = 1000$ passengers
- $F_\alpha(\alpha)$ truncated exponential distribution (over $[0,1]$)
  - $\theta \approx E[\alpha]$ for values $\theta < 0.1$
- Passengers arrive as a Poisson process
  - $\lambda = 2.5$ passengers/minute
- Exponential service times
  - $\mu_1 = 3$ passengers/minute, $\mu_2 = 1$ passengers/minute
- Security levels
  - $L_1 = 0.75$, $L_2 = 0.9$ (class 2 more secure than class 1)
- Capacities
  - $c_1 = 60$, $c_2 = 40$
Static Analysis for $M = 2$ Class Security System

- Minimizing $E[W]$ does not simultaneously minimize $\text{Var}(W)$
Dynamic Analysis

- Effect of cost weight $\eta_1$
- Expected number of passengers equalized in each security class when $\eta_1 = 0.9$
- Overall security (true alarms) maximized when $\eta_1 = 0$
- Expected amount of time in security system minimized when $\eta_1 = 1.0$
Security System Comparison

- System Security (true alarm rate)
- Selective system designed for maximizing security
- When $\eta_1 = 1$, selective system security is lower since no passengers undergo secondary screening

- Mean time a passenger spends in the security system (minutes)
- Two-class system designed for maximizing passenger throughput
Simulation Contribution

- Simulation is needed to estimate passenger security system sojourn time due to the dynamically evolving security threshold values within the risk-based screening policy.

- Simulation results demonstrate that a **multi-level structure** is designed to expedite screening, while a **selective screening** system increases the probability of detecting threat items.

- Simulation can be used to compare the performance of various alternative security checkpoint designs to analyze the effect on true/false alarm rates and screening times.
Summary

• Aviation Security Application
  – Systematic analysis of the passenger screening process
  – Optimal design of sequential passenger assignment policies
  – Responsively adapt to changing threat environments

• Future Extensions
  – Non-exponential interarrival and service time distributions
  – Explore alternative security system structures
  – Investigate dependency among security classes
  – Incorporate cost associated with resolving alarms (true vs. false)
How to get through airport security without a problem

HAND 'EM OVER...
Thank You
(Xie Xie)

Sheldon H. Jacobson
Simulation & Optimization Laboratory
Department of Computer Science
shj@illinois.edu
https:/netfiles.uiuc.edu/shj/www/shj.html