ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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

---

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

Joint work with Adrian J. Lee (CITERI)
Supported in part by the National Science Foundation **CMMI-0900226**

July 24, 2012

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

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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

www.tsa.gov

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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)

www.tsa.gov

- 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)

www.gesecurity.com

- 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

www.tfhrc.gov

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Current Passenger Screening Programs

www.tsa.gov

- 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)

www.tsa.gov


HAND 'eM OVER...
AIR TRAVEL TODAY
PRIDE
RomeNewsTribune
Cagle cartoons.com


AIRPORT BODY SCAN
Gates 11-30
WHERE DID YOU BUY THESE BOXER SHORTS?
CHAPPATTE

Illinois — University of Illinois at Urbana-Champaign

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*** (**E**ffective)
  - An alarm occurs for a passenger/bag containing a threat item
  - Correctly identifies a potential terrorist attack
- ***False Clear*** (**P**erilous)
  - No alarm occurs for a passenger/bag containing a threat item
  - Incorrectly allows a potential terrorist to enter the airport terminal
- ***False Alarm*** (**I**nefficient)
  - An alarm occurs for a passenger/bag containing no threat items
  - Requires additional screening, cost, time
- ***True Clear*** (**C**onvenient)
  - No alarm occurs for a passenger/bag containing no threat items
  - Correctly clears nonthreatening passenger

Designing Effective Screening Systems

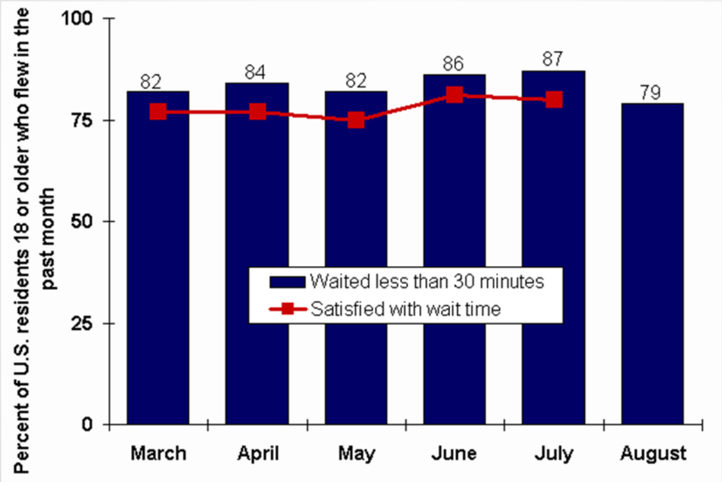
- Challenges
  – Budget limitations, time consuming, questionable effectiveness
- Improving security screening systems
  – Screen high-risk subjects with expensive, low throughput devices
  – Design ***layered*** approach to screening passengers, baggage and cargo
  – Assign passengers, baggage, cargo based on ***perceived risk***
- Modeling Approach
  – **Real-time dynamic model**
  – Maximize security, subject to device constraints

www.tsa.gov

Motivation

Objectives

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



Bureau of Transportation Statistics, 2002, www.bts.gov

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

Setting and Notation

- Queue capacity c_m for security class $m = 1,2,\ldots,M$
- Assessed threat value α_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)

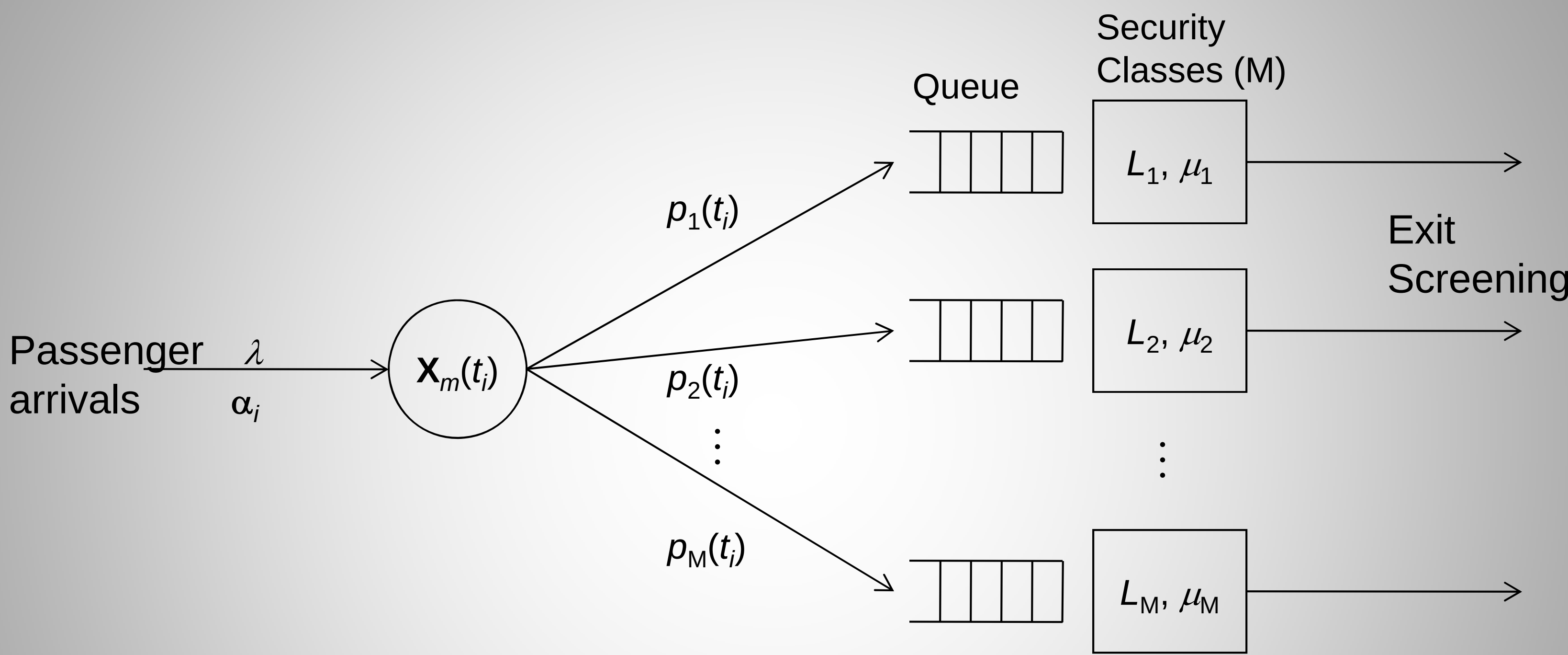
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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*

$$p_m(t_i) \equiv P(\mathsf{X}_m(t_i) = 1)$$

Multi-level Security Class System



- c_m: Queue capacity for security class m =1,2,…,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
  - $\boldsymbol{N}^a(t)$ Number of passengers that arrive for screening **by** time *t*
  - $\boldsymbol{N}_m{}^a(t)$ Number of passengers assigned to class *m* **by** time *t*

$$N^a(t) = \sum_{m=1}^{M} N_m^a(t)$$

  - $\boldsymbol{N}_m{}^d(t)$ Number of passengers screened in class *m* **by** time *t*
  - $\boldsymbol{S}_m(t)$ Number of passengers in security class *m* **at** time *t*

$$S_m(t) = N_m^a(t) - N_m^d(t)$$

One-Step Analysis

- $\{\mathbf{N}_m^a(t),\ t \geq 0\}$, $m = 1,2,\ldots,M$ independent Poisson processes, with rate λp_m, where $p_m \equiv P(\boldsymbol{X}_m(t_i) = 1)$
- Probability transition rates (Chapman Kolmogorov Equations)

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

$$\frac{d}{dt}P(S_m(t)=s_m) = -\lambda p_m\left(P(S_m(t)=s_m) - P(S_m(t)=s_m-1)\right)$$
$$+\mu_m\left(P(S_m(t)=s_m+1) - P(S_m(t)=s_m)\right), \qquad s_m \geq 1$$

- Steady-state probabilities

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

- Geometric distribution

$$P_s^m = \left(1 - \frac{\lambda p_m}{\mu_m}\right)\left(\frac{\lambda p_m}{\mu_m}\right)^s, \qquad \lambda p_m < \mu_m$$

Expectation and Variance

- Standard Queueing Results for Security Class *m* = 1,2,…,*M*
  - $\boldsymbol{S_m}$ = Steady-state number of passengers in security class *m*

$$E[S_m]=\frac{\lambda p_m}{\mu_m-\lambda p_m},\qquad Var(S_m)=\frac{\mu_m\lambda p_m}{(\mu_m-\lambda p_m)^2}\qquad \lambda_m<\mu_m$$

  - $\boldsymbol{W_m}$ = Steady-state amount of time a passenger spends in class *m*

$$E[W_m]=\frac{1}{\mu_m-\lambda p_m},\qquad Var(W_m)=\frac{\mu_m}{\lambda p_m(\mu_m-\lambda p_m)^2}\qquad \lambda_m<\mu_m,\quad p_m\neq 0$$

  - Security system

$$E[S]=\sum_{m=1}^{M}E[S_m],\qquad Var(S)=\sum_{m=1}^{M}Var(S_m)$$

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

- 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* $\Rightarrow$ $\boxed{p_m = \frac{\mu_m}{M\bar{\mu}}}$

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

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

- Equalize E[**W**$_m$] across *m* = 1,2,…,*M* $\Rightarrow$ $\boxed{p_m = \frac{1}{\lambda}(\mu_m - \bar{\mu}) + \frac{1}{M}}$

$$E[S] = \frac{M\lambda}{M\bar{\mu} - \lambda} \qquad Var(S) = \left(\frac{M}{M\bar{\mu} - \lambda}\right)^2 \left(M\sigma_\mu^2 + \lambda\bar{\mu}\right)$$

$$E[W] = \frac{M}{M\bar{\mu} - \lambda} \qquad Var(W) = \left(\frac{M}{\lambda(M\bar{\mu} - \lambda)}\right)^2 \left(M\sigma_\mu^2 + \lambda\bar{\mu}\right)$$

Static Passenger Queueing Problem (SPQP)

- Minimize expected passenger security sojourn time, $E[\mathbf{W}]$

$$\min imize \qquad \sum_{m=1}^{M} \frac{p_m}{\mu_m - \lambda p_m}$$

$$\begin{aligned} subject\ to \qquad & 0 \le p_m \le 1 && m = 1,2,\ldots,M \\ & p_m < \mu_m / \lambda && m = 1,2,\ldots,M \\ & \sum_{m=1}^{M} p_m = 1 \end{aligned}$$

- Solve nonlinear program (NLP) for $p_1, p_2, \ldots, p_M$
- Second inequality constraint replaced with $p_m + \varepsilon_m \le \mu_m / \lambda$
  - 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 $(t_i, t_{i+1}]$

$$N_m^s(t_i, t_{i+1}) = N_m^d(t_{i+1}) - N_m^d(t_i)$$

  - 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

$$P\left(N_m^s(t_i, t_{i+1}) = n_m^s \middle| S_m(t_i) = s_m\right) = \begin{cases} e^{-\mu_m \delta_{i+1}} (\mu_m \delta_{i+1})^{n_m^s} / n_m^s! & if\ n_m^s < s_m \\ 1 - \sum_{n_m^s = 0}^{s_m - 1} e^{-\mu_m \delta_{i+1}} (\mu_m \delta_{i+1})^{n_m^s} / n_m^s! & if\ n_m^s = s_m \\ 1 & if\ s_m = 0 \end{cases}$$

Markov Chain

- Model as discrete-time, inhomogeneous Markov chain

$$P_m^{k,j}(t_i)=\begin{cases}(1-p_m(t_i))P\left(N_m^s(t_i,t_{i+1})=k \mid S_m(t_i)=k\right) \\ \quad +p_m(t_i)P\left(N_m^s(t_i,t_{i+1})=k+1 \mid S_m(t_i)=k\right) & for\ \ k=0,1,\ldots,c_m,\quad j=0 \\ p_m(t_i)P\left(N_m^s(t_i,t_{i+1})=0 \mid S_m(t_i)=k\right) & for\ \ k=0,1,\ldots,c_m-1,\quad j=k+1 \\ (1-p_m(t_i))P\left(N_m^s(t_i,t_{i+1})=k-j \mid S_m(t_i)=k\right) \\ \quad +p_m(t_i)P\left(N_m^s(t_i,t_{i+1})=k-j+1 \mid S_m(t_i)=k\right) & for\ \ k=1,2,\ldots,c_m,\quad 1\le j\le k \\ P\left(N_m^s(t_i,t_{i+1})=0 \mid S_m(t_i)=k\right) & for\ \ k=j=c_m \\ 0 & otherwise\end{cases}$$

- Boundary condition

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

- States s_m = 0,1,…,c_m positive recurrent and aperiodic

Closed-Form Recursions

- Expected number of passengers in security class *m*

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

  – 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*

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

  – Boundary condition, E[**W**$_m$(t_1)] = 1/μ_m

- Security class threshold values

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

Cost Function Components

- False Clears

$$C^Z(t_i) \equiv \left(1 - \sum_{m=1}^{M} \frac{L_m - L_1}{L_M - L_1} p_m(t_i)\right)^2$$

- Passenger Sojourn Times

$$C^W(t_i) \equiv \left(\frac{\sum_{m=1}^{M} p_m(t_i) E[W_m(t_i)] - \omega^*}{\max_{m=1,2,\ldots,M} \{E[W_m(t_i)]\} - \omega^*} \right)^2$$

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

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

$$C^P(t_i) \equiv \frac{1}{M-1} \sum_{m=1}^{M-1} \left(1 - \frac{p_m(t_i)}{p^*}\right)^2$$

where $p^* = \max\{p_m^*\}$

Dynamic Passenger Queueing Problem

- Total Weighted Cost Function
  - $0 \le \eta_1 \le 1, \; 0 \le \eta_2 \le 1$

$$
\begin{aligned}
\text{minimize} \quad & C(t_i) = (1-\eta_1)C^Z(t_i) + \eta_1\big((1-\eta_2)C^W(t_i) + \eta_2 C^P(t_i)\big) \\
\text{subject to} \quad & 0 \le p_m(t_i) \le 1, \qquad m = 1,2,\ldots,M \\
& \sum_{m=1}^{M} p_m(t_i) = 1
\end{aligned}
$$

- Solve nonlinear program for $p_1(t_i)$, $p_2(t_i)$, …, $p_M(t_i)$

Simulation Model

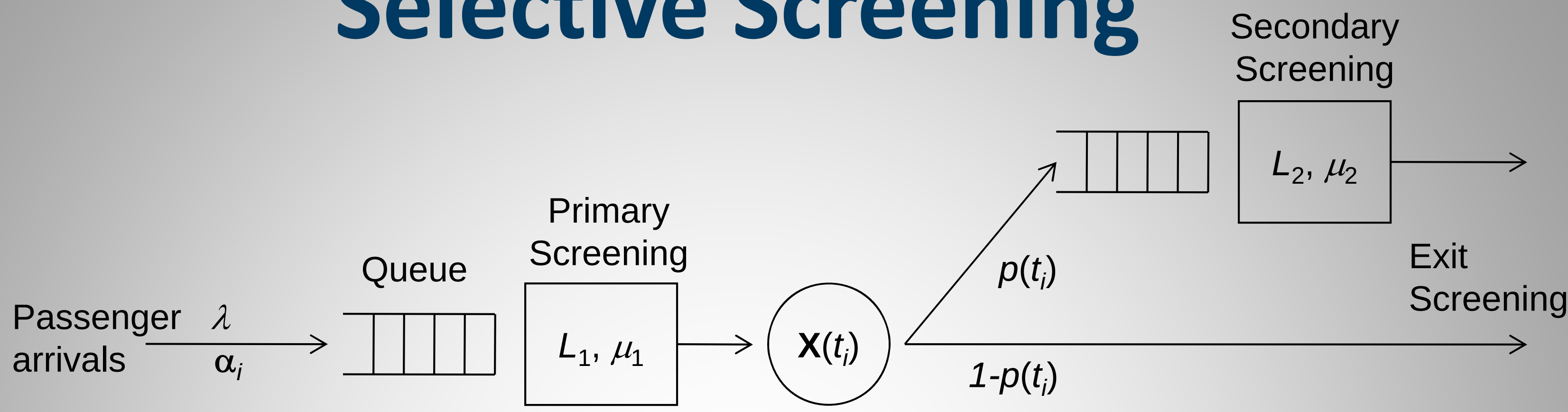
Used to compare security screening policies and conduct sensitivity analysis on the objective function parameters.

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

$$p^*(t_i) = \begin{cases} \dfrac{1-\eta_1}{1-p_s} & if\ S_2(t_i) < c_2 \\ 0 & otherwise \end{cases}$$

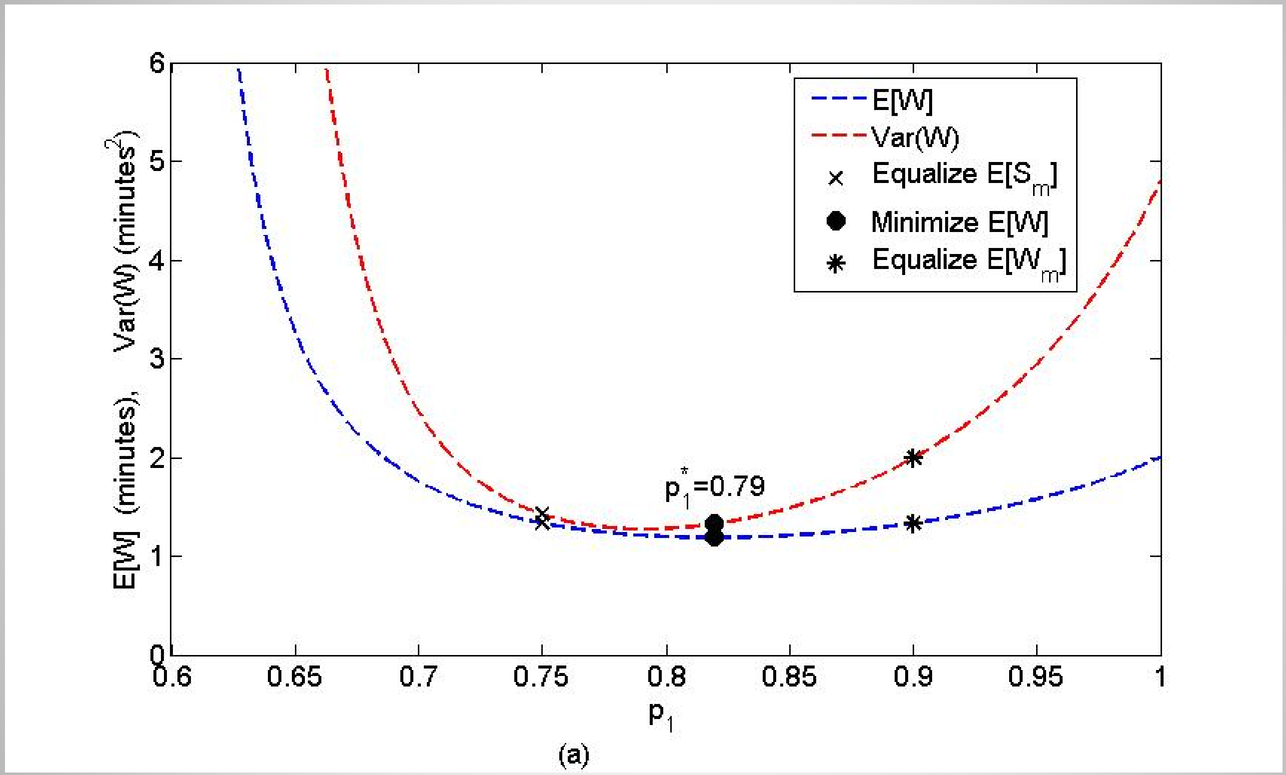
  - Selectees, $p^*(t_i) = 1$
  - p_s = fraction of passengers designated as selectees

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Simulation Results

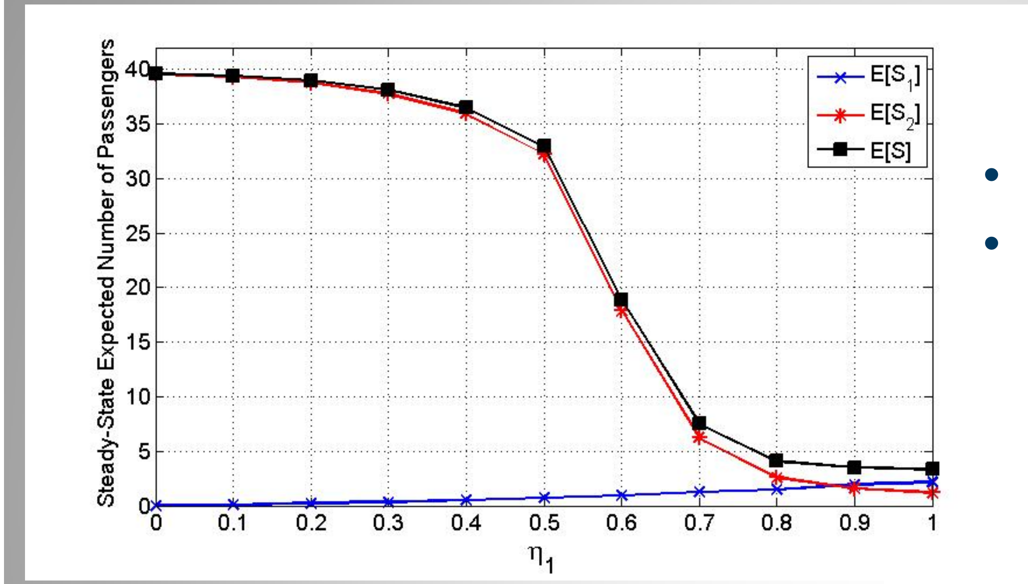
- $M = 2$ class security system, with $N = 1000$ passengers
- $F_\alpha(\alpha)$ truncated exponential distribution (over [0,1])
  - $\theta \approx E[\alpha]$ for values $\theta < 0.1$
- Passengers arrive as a Poisson process
  - $\lambda = 2.5$ passengers/minute
- Exponential service times
  - $\mu_1 = 3$ 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



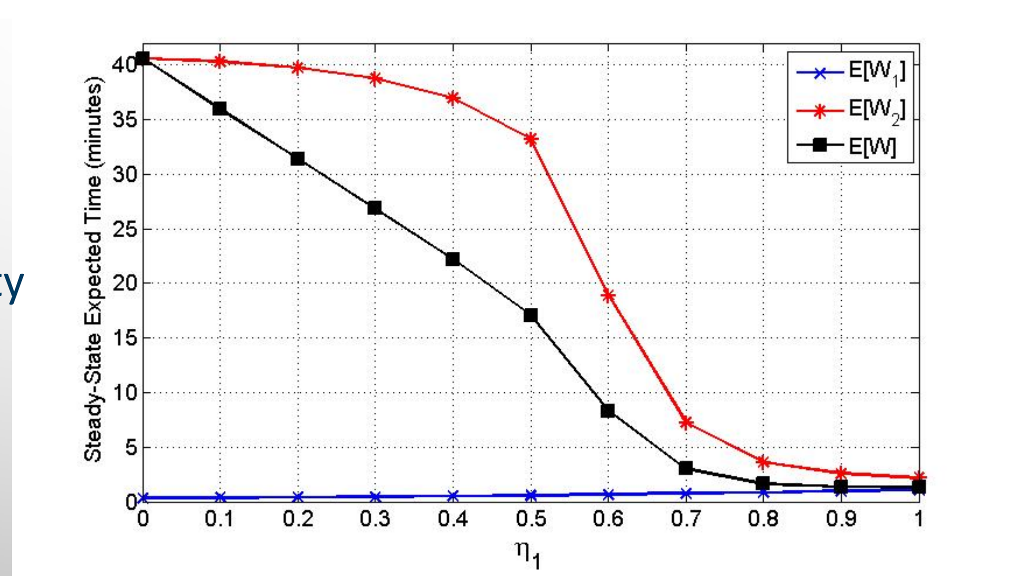
- Minimizing E[**W**] does not simultaneously minimize Var(**W**)

Dynamic Analysis

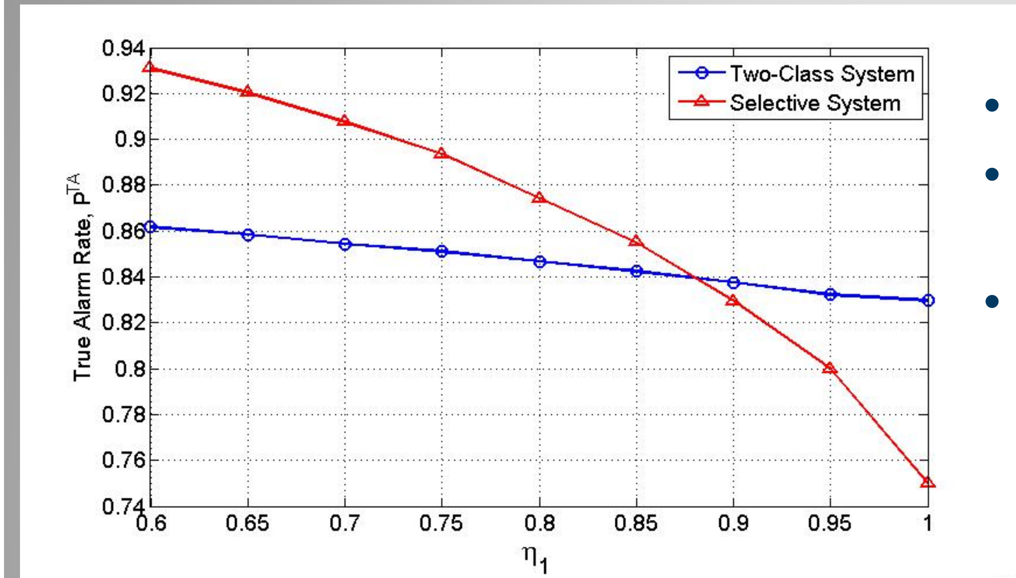


- Effect of cost weight η_1
- Expected number of passengers equalized in each security class when η_1 = 0.9

- Overall security (true alarms) maximized when η_1 = 0
- Expected amount of time in security system minimized when η_1 = 1.0

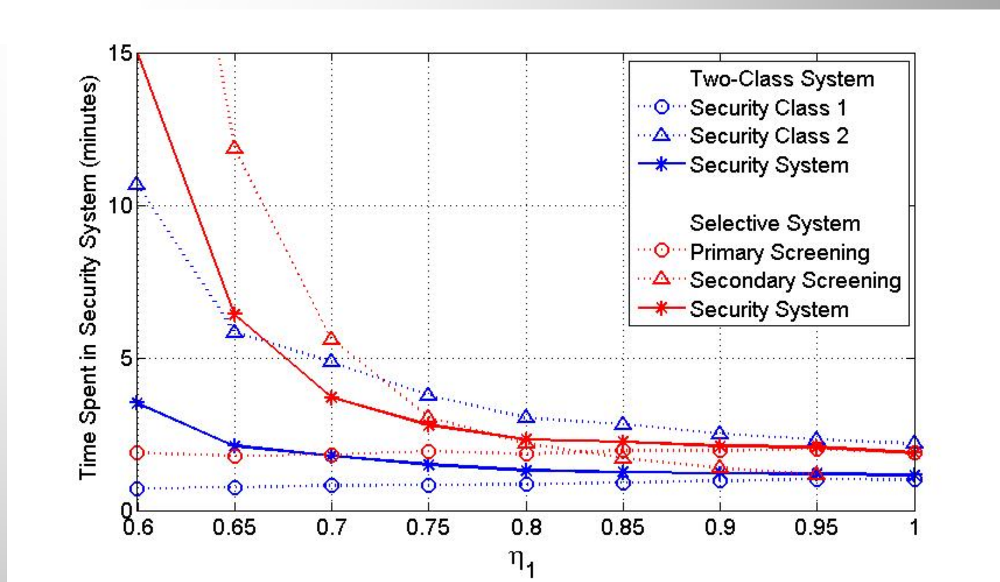


Security System Comparison



- 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

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

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN