Judges' Commentary: Optimizing Passenger Throughput at Airport Security

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Introduction

The 2017 ICM Network Science / Operations Research Question, Problem D, challenged teams of students to analyze airport passenger security, identify bottlenecks, and make recommendations to alleviate delays and minimize the variance of wait times, in an effort to improve the passenger experience while maintaining safety standards. As with all ICM questions, this question had students apply their problem-solving and reasoning skills in the context of modeling to address an issue inspired by the real world. Given the time limitations of the competition, teams had to leverage individual strengths so that they could complete the modeling tasks, write a clear and convincing 20-page report detailing their work and their findings, and still balance other demands on their time, including sleep.

Problem Overview

Following the attacks on September 11, 2001, the U.S. Transportation Security Administration (TSA) has implemented various security measures in an effort to keep commercial airlines safe from terrorist attacks.

However, the imposed security measures can cause significant airport delays and inconvenience for passengers. In the past few years, there have been a growing number of media reports about long security lines leading to missed flights. As passengers try to adjust their behavior to avoid missed

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flights, many show up early, contributing to even longer lines and increasing the unpredictability and variability of the wait times.

This year's Problem D provides a small set of real data collected from a TSA screening checkpoint, along with a description of the current screening process. Teams are then asked to

- create a model of passenger flow through the checkpoint,
- use that model to identify bottlenecks in the current system,
- propose and analyze potential modifications to the current system,
- perform a sensitivity analysis based on various cultural norms and/or passenger types, and
- recommend policy and/or procedural changes that could be employed to reduce wait times and variability in wait times,

all while maintaining the same level of security.

The full problem statement is given in the Contest Report of this issue.

Judges' Criteria

Due to the broad scope of the problem, many teams failed to address all aspects, and this was a primary reason for papers to be eliminated during the triage rounds. However, some papers that did an incredibly clever job on at least some aspects of the question did advance to the finals.

The final judging panel had engineers, social scientists, network scientists, and applied mathematicians from industry, government, and academia, who were all impressed by the diversity of approaches and the high quality of writing from the top teams. Given the high standards, the judging panel specifically sought papers that addressed and communicated the following:

- an executive summary, including the findings;
- a model to measure and assess the flow of passengers through airport security such that bottlenecks could be identified;
- a way of using the provided data to feed or populate the flow model;
- a set of potential modifications to the system, and an analysis to demonstrate the impact of those modifications;
- a sensitivity analysis centered on passenger-based characteristics, such as cultural difference, group size, or efficiency in moving through the line;
- an overall set of recommendations that were both:
  - based on the analysis presented in the paper, and

– presented in a way that considered the feasibility such as budget, personnel, and space constraints.

In the sections below, we offer commentary on the components of the problem and offer strong examples from this year's submissions.

Exposition

While the quality of the modeling is very important, it is perhaps even more important that the work is communicated in a clear and convincing manner. Occasionally, the judges see papers that appear to have applied very advanced mathematical techniques, but the writing does not justify the use of that model. Similarly, a team might produce numerous results; but if those results are reported only in a large paragraph filled with undefined symbols and never put into context, then the value of those results is lost. Conversely, even a simple model can be powerful if the design of the model is well-reasoned, the simplifying assumptions and their expected impact on the results are discussed, and the results are explained in a meaningful way, which often includes some data visualization. Perhaps the most important portion of the paper, the executive summary, is a place where teams have a chance to really demonstrate their strong exposition skills, as this one page description needs to introduce the problem, overview the methodology, and highlight the key findings.

Modeling Approaches

Given the open-ended nature of ICM questions, teams can be successful in applying a wide range of modeling approaches.

The first step in modeling this problem required teams to determine how to use the data provided on passenger arrivals and screening times. The majority of teams realized that they could perform statistical analyses on the columns of provided data to determine the most reasonable distribution type, and then they could generate a larger data set based on the distribution. However, other teams made strong arguments that even a Poisson distribution would still give unreasonably large values, albeit rarely, and so they artificially truncated the distributions or applied triangle distributions.

Once armed with passenger arrival and processing distributions, teams developed models to analyze the passenger flow through TSA security. Many teams applied queuing theory with Petri nets. Another common approach was the use of discrete event simulators; some teams wrote their own in MATLAB, while others found and used existing software packages. However, the judges also saw creative and valid approaches such as agent-based models, partial differential equations, and even Ohm's law (relating electrical current, resistance, and voltage). Using these models, the teams identified bottlenecks in the current TSA screening process. Some teams went further to explore how their existing process would be impacted based on the time of day and number of flights at that time at the airport.

After analyzing the flow and identifying the bottlenecks, teams then had to propose and test possible improvements as well as explore the impact of different passenger types. Both of these tasks required teams to consider potential changes to the screening process in the real world and how those could be represented in their models. While many teams analyzed the impacts of a limited and distinct set of modifications, other teams performed thorough optimization analyses on issues such as the ratio of PreCheck lanes to regular lanes and the ratio of luggage screeners to ID-check lines. To study the impact of passenger type, some teams explored cultural differences, such as whether or not it was acceptable to cut or skip places in line, while others injected a mix of passenger profiles, such as suspicious passengers, business travelers, or slower travelers with lots of luggage.

Teams were asked to make recommendations to the TSA security managers. The judges were pleased to see teams make recommendations that were supported by the analyses presented in their papers. Many teams suggested adding lanes or increasing the number of staff, but the strongest recommendations also took into consideration factors such as cost and space limitations. Several teams also considered human factors, such as having a virtual queue in which passengers would still need to wait but would be free to explore restaurants and shops until their designated screening time.

Discussion of Outstanding Papers

Ultimately, out of a pool of many strong modeling approaches leading to a diverse set of high-quality recommendations, five papers were selected to receive the distinction of Outstanding. These papers are representative of the wide array of possible modeling approaches, and they all do an excellent job of relating the real world to their model and its results. Discussions of each of the five Outstanding papers follow.

Shanghai Jiao Tong University, China

"Breezing Through Security Checkpoints: An Intelligent Airport with Smart Scheduling"
Leonhard Euler Award

Shanghai Jiao Tong University had two teams this year with Outstanding papers for this problem. The model in this paper used queuing networks and routing algorithms to study and make analysis-based recommendations to the passenger screening process. Throughout the paper, the exposition was very clear, and the team did an excellent job of explaining how their modeling decisions and parameters corresponded to the screening process in the real world. They began their analysis by using the built-in functionality in Mathematica to estimate the distributions for passenger arrival and servicing times, based on the provided data sets; they supported their decisions by including a visual comparison of the given data and the distributions that were produced. The team then used these distributions to set up a first-in, first-out (FIFO) queue that was fed by a Poisson arrival rate of passengers who were moved through the queue based on a normal distribution for servicing times. In order to make sure that the passenger line didn't continually grow, the team performed a rate stability analysis to determine the number of lanes that were necessary for ID checks and for bag checks for regular passengers, and then they applied the problem-quoted 3:1 ratio to determine the number of corresponding PreCheck lanes.

One thing that was particularly strong in this paper, and surprisingly not very common in the field of submissions this year, was the explicit inclusion of a defined set of performance metrics, including the introduction of the terminology, a mathematical equation for each metric, and a written description justifying the choice of the metric in the context of the problem. In this case, the team selected *throughput*, as a collective measure of the speed of the system, and *variance*, as an individual measure of fairness.

After discussing the impracticality of using a tandem queue approach in the context of the real world, the team presented a networked queue, as shown in **Figure 1**. The team also included the injection of random suspicious passengers into this model. The team validated its model by taking real daily passenger totals from five of the largest airports in the U.S., using this information to feed a Poisson arrival of passengers into their model, and then comparing their calculated average wait time with the average wait times reported by those airports. This networked queue with suspicious passengers was then run to determine the baseline metrics of throughput and variance and to identify bottlenecks in the system.

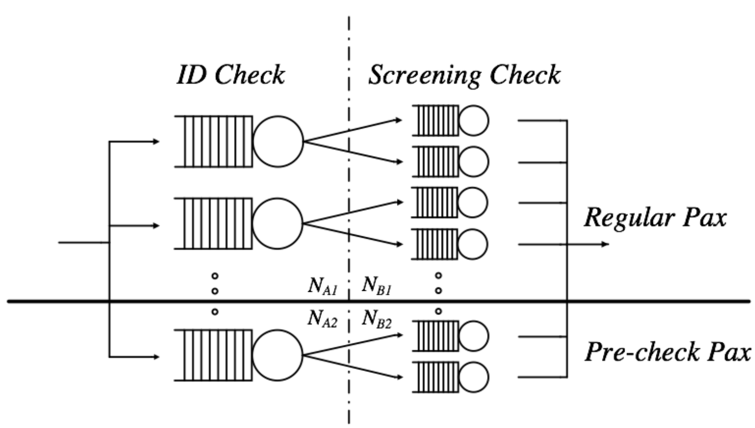


Figure 1. Queuing network model from the Shanghai Jiao Tong University team.

Based on the identified bottlenecks, the team modified the topology of the network and the routing algorithms, and the paper made a strong case connecting the model changes with the corresponding real-world implications. After testing a greedy algorithm based on backlogs of individual lanes, backpressure drift using a Lyapunov function that measured the total queue backlog for the network, and a penalized backpressure drift that emphasized the impact of PreCheck-only lanes, the team explained the relative impacts of each, converting the mathematical results into an explanation in the context of airport security lines.

The sensitivity analysis explored the impact of several cultural and passenger-type norms: collectivists who are willing to sacrifice personal benefit for the global benefit, individualists who prioritize individual efficiency, families traveling together, and individual tech-savvy travelers who adjust their airport arrival based on real-time information about the length of the queue. After explaining how each of these norms related to a specific parameter in the model, the impacts of varying each parameter were discussed, with the mathematical results presented graphically and supported by a meaningful analysis of how these findings related to actual passenger behavior and the resulting throughput and variance.

After addressing their model's strengths and weaknesses, the paper closed by presenting a set of global recommendations, as well as airport-specific recommendations based on its passenger norms. Unlike many of the successful participation papers, these recommendations were completely based on, and supported by, the analysis in the paper.

Shanghai Jiao Tong University, China

"Analysis and Optimization to the Process of Airport Security Check"[1]

This paper, also from Shanghai Jiao Tong University, opened with a very clear summary. Recognizing that they did not need to start from scratch, this team started their work with a review of the literature about work that had already been done to understand airport security lines and ultimately based their work on the queuing theory ideas they discovered.

The list of assumptions was extensive and included justifications for each, including an assumption about the arrival and processing distributions. Unlike many teams that performed a statistical analysis of the given data to determine the distribution type, this team discussed the nature of each process and selected a distribution type from a first-principles perspective, using the provided data only to fit the parameters of those distributions. The team also made an assumption about the relationship between the number of bags a passenger carries and the amount of time needed to prepare those belongings for screening.

In the first step of their model, the team generated the arrival of passengers based on a Poisson distribution, arguing that the arrivals are independent of one another. Then each arriving passenger was assigned

[1]This paper appears in this issue of *The UMAP Journal.*

attributes. These attributes included the bag preparation time, which was based on another randomly assigned attribute, the number of bags. The attributes also included an ID-check time and a millimeter-wave screening time, which were based on Gaussian distributions; the team argued that TSA agents should be competent, so the time to do their job should be centered normally around a mean. These properties were all fed into the team's queuing model, which outputted the wait-time data, including the mean and variance. When the team plotted the histogram of the wait times, they noticed that the distribution was nearly uniform, meaning that there was high variability in the wait times. Based on the results from this initial analysis, the team also identified bottlenecks. In order to understand, and ultimately support the 3:1 ratio of regular lanes to PreCheck lanes, the team explored the impact of varying the ratio of PreCheck lanes to regular lanes while holding the ratio of PreCheck passengers to regular passengers constant. They also looked at the reverse, by varying the passenger-type ratio while holding the lane-type ratio constant.

Based on the findings from the initial analysis, the team made three recommendations and tested them.

- They added a link to their model that represented the addition of a bag-preparation staging area in which several passengers could get their things ready at once, and whoever finished first would be able to advance, making space for someone else to prepare their items.
- They modified their queuing algorithm with the addition of an emergency lane to accommodate passengers at risk of missing their flight, both those arriving at the airport late and those who had already been in queue for some time but are now at risk of missing the flight.
- The team modified the model to treat elderly and children as if they were PreCheck, since the TSA passed a rule that does not require these passengers to remove shoes or light jackets.

For each of these modifications, the team ran an optimization analysis to determine the parameters that would best reduce the mean and variance of wait time.

In order to test the stability of the model, the team adjusted their model to analyze security at Chinese airports. They added a cut-in-line feature in which passengers could randomly cut in line anywhere, not just at one space. They also modified the model to treat all passengers as PreCheck, since China does not require passengers to remove their shoes or light jackets. The findings, including the efficacy of some of the wait-reducing measures, held in this new situation, demonstrating a robustness of the methodology across cultural differences.

The team presented a set of conclusions that were based on their analysis, although the team raised concerns, as did the judges, about the validity of the assumption about the elderly not having luggage, and this assumption directly led to one of the recommendations. However, overall, this team demonstrated strong modeling and clear justifications that connected their work with the real world.

NC School of Science and Mathematics, North Carolina, USA

"Optimizing Passenger Throughput at an Airport Security Checkpoint"

This high school team's paper started strong with a well-written summary that included an overview of the problem, the analysis, and the findings. The restatement of the problem included references that justified the significance of their work in the context of the purpose and importance of the screening process. The list of assumptions was thorough, and each assumption was justified in terms of its necessity to make the model work and its relationship to the real world. While many teams used discrete models that assumed solo passengers, this paper was one of only a few that explicitly stated the individual traveler assumption.

The team started their work by analyzing the given data. They performed Shapiro-Wilk normality tests and used quantile-quantile plots to discover that two of the processes could be represented well with normal distributions. For the remaining processing times, the team performed their own experiments and used online video footage of real airport screening checkpoints. For the arrival rates, the team used the given data to calculate a *generation probability*, which represented the likelihood of a passenger to appear in that second. The team also assigned probabilities for pat-downs and bag searches based on whether a passenger was a regular passenger or a PreCheck passenger.

The judges were impressed that the team accounted for the fact that different staffing levels and differing number of lanes required would vary based on time of day and level of activity of the airport. They ran tests at different generation probabilities and with different configurations to better understand the capacity of each configuration to handle low, medium, and high flows of passengers.

The team used NetLogo to build an agent-based model that simulated the behavior of passengers and TSA screeners as the passengers moved through the queue. After testing the model and developing a baseline, the team then proposed and tested six different modifications. The descriptions of the modifications included both the real-world driver for the change, the real-world outcome of the change, and how the model could be modified to reflect that change. For example, one of the modifications was to train the TSA agents on pat-downs to make them faster, and this modification was reflected by changing the average pat-down time in the model. The results of the modification analysis were compared in an easy-to-read table accompanied by a clear and detailed description that put the numerical results into the context of the the TSA screening process. For the passenger behavioral sensitivity analysis, the team examined the effect of passengers cutting lines, moving slowly due to age, and asking for pat-downs more frequently, based on a source stating this behavior was expected due to concerns about the millimeter-wave scanner.

The paper included its policy recommendations based on the analysis, but the judges did notice that the recommendations addressed the need for more personnel and equipment without a lot of concern expressed about the increased cost. The paper closed with a reflective assessment of the strengths and weaknesses of the model, as well as ideas for future directions for this work.

Brown University, Providence, Rhode Island, USA

"Reducing Wait Times at Airport Security"

This paper from Brown University's team provides an example of a more theoretical approach that was strongly justified with exposition relating the analysis to the real world. The paper's executive summary was very clear and concise, and the main paper opened with a restatement of the problem and an overview of the team's approach. A short set of justified assumptions were provided at the front of the paper, but as the model developed and evolved, additional assumptions were introduced and rationalized.

To start the analysis, the team fit exponential distributions to the arrival data for regular and PreCheck passengers, and they applied kernel density approximation to fit a probability distribution to the identification check processing times for each of these types of passengers. The team also used kernel density estimation, as well as the independence of the luggage screening processing times and the millimeter wave scanning processing times, to obtain an overall processing time for these two parts of the passenger screening process.

The team then presented the full derivation of a theoretical model using a recurrence relation for the total wait time by a passenger, based on the probability distribution functions for the arrival and processing times of the queue. This approach led to an explicit formula for the wait time of the nth passenger. They also develop a dynamic programming approach to run numerical simulations. After comparing the results of the theoretical model and the simulation, the team then identified bottlenecks and modified the simulation to explore the impact of potential improvements to the screening process.

While many teams performed simulation experiments to understand the impact of varying the number of TSA agents and lanes, only a few discussed the cost; and this paper provided the most thorough cost-benefit analysis seen in final judging. The team noted that the TSA earned a fee for every passenger processed, but that there was also a personnel cost associated with opening additional lanes. These factors allowed the team to write down a cost-benefit function that could be optimized based on the number of each type of lane that was open.

The sensitivity analysis assessed slow (or inexperienced) passengers versus fast (or experienced) passengers. The team also explored the idea of clustering types of passengers through the use of virtual queuing, in which passengers would be given a time to report back for scanning, as opposed to waiting in a physical queue.

Due to the theoretical approach of the team, the generalizable results were distributed throughout the paper, but the judges wished that an example case had been included in the conclusions. Instead, the paper closed with some meaningful suggestions about how the team could improve their model and how their work could be generally applied.

Zhejiang University, China

"Time Counts! Less Waiting & Better Airports"
INFORMS Award

This paper from Zhejiang University opened with a restatement of the problem that justified the importance of the work in the context of security, followed by a brief synopsis of their work and a supporting infographic.

Like many teams, this team used the existing data to fit parameters to a probability distribution to input into a queuing model. However, this team also took note that the data included values for different TSA officers, and therefore they applied a statistical significance test to verify their assumption that the servicing variability of individual TSA officers did not significantly contribute to the variance of screening time.

For the queuing model, they put two queues in series, with the first being a Poisson service to represent arriving passengers getting their identification checked, and the second being an Erlang k-type service whose arrival rate was given by the processing rate of the first queue. Since an analytical solution of their queue was not possible, the team built a numerical simulation of the queue in MATLAB to calculate the wait times, as well as the mean and variance of the wait times. This model provided insight that the screening was the greatest bottleneck in the system.

While many teams examined the impact of adding additional lanes, this paper presents a financial argument that adding one scanning lane is similar to adding four ID check lanes, and this ratio was used in their analysis of the relative impact of adding lanes.

The team then shifted focus to explore passenger arrival behavior. Rather than simply using an exponential model for interarrival times, the team assumed a normal arrival distribution around a mean of the recommended TSA arrival time. They then took actual flight data, including aircraft size and departure times, for one day from Chicago's very busy O'Hare airport and applied their assumed arrival behavior to create a new arrival rate distribution that was then fed into their queuing model. The team explored how the results changed as the recommended arrival time changed. This work also tied into work the team did on cultural punctuality, in which they showed that nations with a cultural reputation of being less punctual actually cause large spikes in airport lines near take-off, and that this drives up the variability in the required number of queues for short bursts, which causes human resource issues for the security office.

The team also proposed that checkpoints be consolidated or that passengers be able to see a sign showing the estimated queue lengths at different checkpoints throughout the airport, as this should allow passengers to self-regulate and choose shorter lines. While the judges saw similar recommendations in other papers, this paper actually supported the team's intuition with a mathematical justification based on a proof from queuing theory.

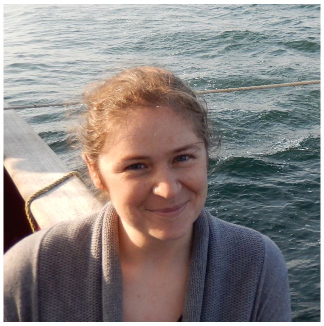
Another recommendation involved the use of virtual queuing with priority given based on flight departure time, or a hybrid system that used both actual airport arrival time and flight departure time to suggest a screening time. The team built an *acceptability parameter* into this hybrid system that could be changed to account for different cultural reactions to having priority given by flight departure time versus passenger arrival time.

To test the sensitivity of the model, the team ran their model with incremental adjustments in passenger flow and servicing times for each of the two queues. The team ended their paper with a clear set of recommendations in the form of a notice to security managers, followed by a discussion of the strengths, weaknesses, and areas of future work for their model. Overall, the judges were impressed by the diversity of angles that were addressed by this paper and the depth it offered in exploring those angles.

Conclusion

While the judges expected most papers to take a straightforward queuing theory approach to this question, they were excited to see a lot of diversity in the approaches taken, including some that were completely unexpected yet absolutely valid. Also, each team brought their own strengths, with some teams embracing the unpredictability of human behavior in stochastic models and others addressing the problem in a more theoretical and deterministic approach that allowed them to identify larger trends that rose above the noise of that variability; some performed their sensitivity analysis with an impressive understanding of cultural and societal norms while others built cost-benefit analyses from an informed business perspective. It is important to note that not a single team did everything well or completely. In fact, this is the beauty of this competition and of real life—that we are never done answering all the questions, and there is always room to explore more in many directions.

About the Author



Jessica Libertini holds advanced degrees in both Applied Mathematics and Mechanical Engineering. Jessica is on the faculty at Virginia Military Institute, where she actively engages students in a variety of applied mathematical and educational research topics, both in the classroom and beyond. To contextualize mathematical concepts for her students, Jessica draws heavily on her industry experiences working with General Dynamics, the Missile Defense Agency, the National Research Council, and the Army Research Laboratories. She is involved in the development of classroom materials to support the teaching and learning of mathematical modeling, and her two most active research interests are K-16 STEM education and multi-scale mathematical and network-based modeling of food and health systems.