



Expediting airport security queues through advanced lane assignment

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Abstract

Excessive airport security wait times during peak operational periods have been well-documented in crowdsourced data and well-publicized among the news media. While serving a paramount purpose, airport security checkpoints are capacity constrained and frequently stressed, leading to passenger dissatisfaction and system limitations. To alleviate air travelers' wasted wait time during the security screening process, an innovative queue management technique is explored. Passengers currently flow to Transportation Security Administration (TSA) screening lanes at terminal checkpoints via a First-Come, First-Serve (FCFS) discipline. However, repeated variations in passenger characteristics and screening times may cause this service discipline to suffer small inefficiencies that aggregately distort resource utilization and throughput speed. This paper proposes an Advance Lane Assignment System (ALAS) in which passengers are directed to specific screening lanes upon arrival to a terminal checkpoint using real-time, autonomous, feedback control. Leveraging existing Bluetooth[®] technology to assess lane flow rates, control logic can convey lane assignments to passengers at identification authentication gates. System feasibility was analyzed through discrete, dynamic, and probabilistic simulations of a multilane, multiphase queue model with varying traffic intensities and control logic. Basic, discrete-time Proportional-Integral-Derivative (PID) control was found to offer a 12% reduction in average passenger waiting times over the baseline FCFS discipline.

Keywords Airport Security · Security Screening · Advance Lane Assignment · Security Queue

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Introduction

The modern commercial air transportation system is characterized by growing traffic volumes, diminishing land capital, and lingering security threats. Protecting over two million travelers per day across 440 U.S. airports, the Transportation Security Administration (TSA) and its approximately 43,000 officers are the final frontier of safety in America’s skies (TSA 2020a, b). While passenger reductions resulting from the COVID-19 pandemic have reduced screening volumes proportionately, the system is recovering and is expected to continue growing into the future. The unequivocal importance of air travel in today’s economy and society demands strong yet expedient transit security.

Problem scope

Since most commercial air terminals in the U.S. were constructed before the 9/11 attacks, ticketing halls were retrofitted with Transportation Security Equipment (TSE) and accompanying queues. This lack of architectural design for security installations greatly inhibits their capacity by dictating commonly cramped and contoured geometries for screening zones. Current passenger inspection stations, termed Security Screening Checkpoints (SSCP), are subjected to excessive loading during peak travel times, leading to lengthy passenger lines and subsequent public animosity. Stressed by traffic surges and limited space or personnel, security checkpoints are too often overwhelmed by passenger flows; while many airports’ SSCPs have tolerable average waiting times of between 10 and 20 min, surges in passenger volumes around holidays and schedule banks routinely record unacceptable hour-long queues (Miller 2020).

To better visualize this issue, the researchers collected peak wait times and plotted them against annual enplanements in Fig. 1 for all 130 primary hub commercial

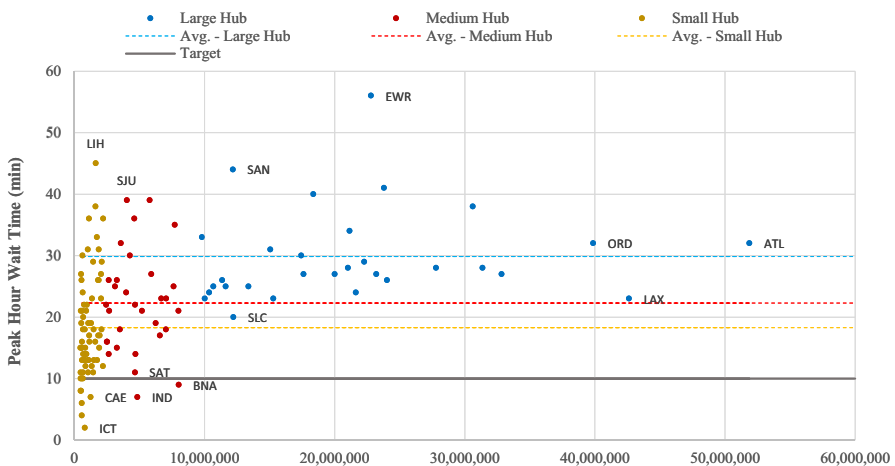


Fig. 1 Security wait times and passenger enplanements by airport

airports in the National Plan of Integrated Airport Systems (Federal Aviation Administration [FAA] 2018). Peak wait times were recorded on January 9, 2020, as the largest hourly wait, from 6 AM to 10 PM, displayed on the 'MyTSA' mobile application; self-reported by passengers, this data includes 56 prior days and is not specific to individual terminals or checkpoints within each airport (Department of Homeland Security [DHS] 2017).

While the TSA aims to limit the average security delay of passengers to 10 min, MyTSA data shows that, during peak airport operational periods, only 11 of the 130 airports met that target (U.S. Congress 1970). Rather, the average peak wait times for large, medium, and small hub airports were computed to be 30, 22, and 18 min, respectively. The slowest security queue was at Newark-Liberty International Airport (EWR), with a 56-min security queue on Monday mornings; relatively well-performing airports included Salt Lake City International Airport (SLC), Nashville International Airport (BNA), Indianapolis International Airport (IND), Wichita National Airport (ICT), and Columbia Metropolitan Airport (CAE). Peak security waits at most commercial U.S. airports result in substantial inconveniences for passengers and inefficiencies for operators.

Although passengers are warned to plan their ground travel accordingly, security screening waits contribute to travelers missing booked flights or deciding against flying altogether, which damages both airline and airport revenues. Sensitivity of some passengers to privacy in advanced identification and imaging technologies also raises concerns with the perception and efficacy of security among air travelers. Due largely to no fault of their own, airport security is unfairly excoriated in the media and flying public as a chaotic and incompetent nuisance rather than respected for its important mission and minute complexities (Frederick-Recascino et al. 2003). With spatial constraints fixed over the near future, security checkpoints will be able to expand capacity primarily by better allocating human and capital resources and harnessing leading-edge automation technologies.

Technological development

Advancements in a variety of screening technologies provide an exciting opportunity to enhance the speed and rigor of airport security without committing to costly and lengthy infrastructure expansion projects. Having commissioned an internal Innovation Task Force (ITF), the TSA has embraced technological development by commencing trials of systems ranging from Biometric Authentication Technology (BAT) to Automated Wait Time (AWT) and Automated Security Lanes (ASL). In a timely search for their Checkpoint of the Future (COF), the TSA has deployed faster and finer Advanced Imaging Technology (AIT) for enriched anomaly resolution and trace determination (Karoly 2017). However, as screening robustness is enhanced through integration of new identification and imaging technologies, operational performance and passenger experience must also be improved rather than compromised.

More so than reducing today's excessive wait periods, tomorrow's airport security must heighten passenger flow to accommodate sustained growth in air travel demand;

the TSA lists enlarging SSCP throughput from 150 to 230 passengers-per-hour-per-lane, a significant 53% improvement, as a core goal of the COF next generation security infrastructure (DHS 2014). Developed in 2012, the AWT program focuses on reporting queue lengths instead of altering queue controls by yielding wait time estimates from signal processing. However, if walking times from AWT screens to SSCP options are similar in order of magnitude to waiting times, the program loses any effectiveness as a feedback control system. Parallel queue reporting systems powered by crowdsourcing are unreliable in that they are subject to response bias of individuals who experienced abnormally long delays. While AWT transparency enhances travelers' cognizance of quickness and directs flow macroscopically between checkpoints, the system is not intended to mitigate small scale inefficiencies among multiple screening lanes of a single checkpoint. Today's SSCPs allow travelers to determine their own flow, choosing a Standard Security Lane (SSL) after passing through a Travel Document Checker (TDC). Rational human behavior theory suggests that individual passengers will join the visibly shortest queue, believing that physical queue length correlates to queue time. In practice over the short-term, however, the former factor varies according to passenger relationships and line geometry while the latter varies by differences in passenger screening times. First, curving line structure and varying line density decrease the correlation between the number of perceived and actual individuals in the queue. Second, diverse passenger characteristics such as age, number of bags, security risk, and travel frequency, among others, decrease the correlation between the number of waiting individuals and the actual wait times. Travelers cannot accurately sense the future movements and current lengths of SSLs and are largely prohibited from switching lanes once in an SSL queue, preventing simple passenger choice from truly translating to a fair and fast First-Come, First-Serve (FCFS) scenario. Rather, two lanes of similar length can have greatly differing wait times so that passengers may unknowingly enter the longer rather than the shorter queue. A striking and accumulating inefficiency, this small-scale phenomenon can aggregately skew lane utilizations and wait times. Rapid, recent strides in screening technology require sophisticated passenger flow control to fully realize operational success in serving record-setting traffic volumes.

System design

An established bottleneck of modern transportation, airport security may be expedited without loss of security stringency through innovative queue management. To optimize mean and median SSCP waiting times during peak travel periods at hub airports, an Advance Lane Assignment System (ALAS) is proposed. Operating independently of security lanes designated for PreCheck travelers and Known Crew Members (KCM), ALAS would distribute passenger flow among multiple security lanes for maximal SSCP throughput and minimal SSCP waiting. As various aforementioned effects confound the assumed correlation between queue size and queue time, FCFS passenger lane choice leads to inflated wait time performance measures. Rather, directing passenger flow across security lane queues of differential lengths and speeds, ALAS would counterintuitively yet intentionally generate lane queues of unequal sizes through real-time, autonomous feedback control. At each SSCP in a terminal, passengers are given,

rather than allowed to choose, a specific screening lane (SL). This ALAS arrangement would supplant AWT in that AWT directs passengers between SSCPs while ALAS would direct passengers between SLs within a singular, large SSCP.

Passengers are assigned a security lane upon clearing a Travel Document Checker (TDC) podium or similarly purposed Biometric Authentication Technology (BAT) gate. While a SSCP queue forms for TDC podiums, from anecdotal experience and historical analysis, the core congestion occurs upon physical screening of passengers and luggage rather than at document checking; the cycle time of a passenger through a TDC is less than the cycle time through SL components (belongings divestment, belongings scan, personnel scan, and belongings revestment areas), so that screenings are the capacity-limiting factor. The security lane is provided to the traveler by an audible, visible, or tangible cue, and would be computed by a feedback control algorithm. This algorithm would estimate individual lane speeds and line lengths by measuring separate security lane traffic through Bluetooth signal intensity, requiring sensors to be placed at the start and end of SLs. A reliable, accurate, and mature technology, Bluetooth as utilized by AWT identifies the presence of passengers through the Media Access Control (MAC) address of their personal, Bluetooth-enabled devices (DHS 2012); the most common devices, smartphones, are ubiquitous among consumers of modern air travel. Run in real-time to replace passenger choice, the algorithm would take security lane Bluetooth signal metrics as input and yield a security lane assignment as output.

ALAS would consist of hardware and software, both of which would be synergetic and scalable with AWT, BAT, and ASL technologies: ALAS sensors would leverage existing AWT Bluetooth identification technology for input, and ALAS algorithms would most efficiently utilize developing BAT gates for output. Bluetooth sensors, of which thousands are already in use in airports and transit centers across the world, are well suited for measuring device, and thus passenger, flow through screening lanes. Such sensors, with reported accuracy rates of up to 95% for slow-moving pedestrian traffic, are field-proven and commercially available, and would capture most travelers entering and leaving queues (Veovo 2014; Hainen et al. 2013). With most SSCPs at congested airport terminals already offering AWT, ALAS could also make use of their Central Control Server (CCS), collocated in the SSCP.

Implemented swiftly and precisely, ALAS would serve as an accelerator between BATs and ASLs in the next-generation airport security COF. The central goal of ALAS is to improve wait times and queue structures by enhancing resource utilization and passenger prioritization. Rather than navigating the tradeoff between security robustness and convenience, this proposal seeks to align these aims in creating a safer and more seamless travel experience for commercial air passengers.

Numerical simulation

Model structure

As applied to complex and dynamic real-world problems, classical queueing theory is frequently found to be impractical in modeling traffic fluctuations.

However, security at modern commercial airports is uniquely suited to analytical queueing models as queueing subjects (passengers) legally lack any alternative and all checkpoint facilities and screenings services are regulatorily uniform (Wilson et al. 2006). Advancements in computing power and control algorithms make simulation an inexpensive and noninvasive method of analyzing alterations to complex and dynamic processes. Airport and airline operations are a well-explored and documented area of queueing theory among researchers in academia and industry alike; simulations are generally discrete, dynamic, and stochastic in nature (Guizzi et al. 2009; Crook 1998). Simulations of the proposed ALAS technology differ categorically from most publicized airport security models of which the authors are aware in that queueing into security lanes, rather than queueing among stages of security lanes, is the focus of control analysis. While the observed security process is multi-channel and multi-phase, the idealized simulations are five-channel and dual-phase so to isolate and analyze queueing logic structures. The number of channels corresponds to the number of SLs within an SSCP while the two phases modelled include primary screening and secondary screening. Primary screening consists of baggage divestment, scanning, and revestment, as well as body scanning, with a Walk-Through Metal Detector (WTMD), X-Ray machine, and Advanced Imaging Technology (AIT) (TSA 2018a). An alarm rate, approximated at a constant 9% in accordance with prior airport security studies, triggers selection of passengers for secondary screening in the simulation (Dorton and Liu 2012; Rizk et al. 2018). The secondary screening consists of a manual inspection of baggage or personnel via Explosive Trace Detection (ETD), a Bottled Liquids Scanner (BLS), and Handheld Wand Metal Detector (HWMD) (TSA 2018b). As passengers prohibited from passing through security are extremely rare and are forced to exit SLs regardless, the simulation does not discriminate between cleared and rejected passengers and assumes that all exit after secondary screening, if applicable. To meet future passenger demand under practical expansion constraints, security checkpoints must utilize automation to grow in terms of productivity rather than size.

Process distributions

Constructed simulations consider various queueing algorithms applied to a standard, multi-lane checkpoint configuration. Processes are modelled as Markov chains in which events have an exponential interarrival time; the entry times of passengers into the SSCP and the service times of passengers through the SSCP are approximated with Poisson and Erlang distributions, respectively. The Poisson probability density function of passenger arrival rates into the security checkpoint (g_i) is characterized by the mean rate of arrival per unit time (λ) and the number of passengers arriving at the security checkpoint (i).

$$g_i(i, \lambda) = \frac{\lambda^i e^{-\lambda}}{i!} \quad (1)$$

Three mean rates, in passengers per hour per lane, were considered: a 200 ‘usual’ rate to represent lane throughput at full capacity, a 250 ‘design’ rate to represent lane throughput at full capacity and tolerable waiting time, and a 350 ‘peak’ rate to represent passenger surges during schedule banks (Fig. 2) (Leone and Das 2010).

The Erlang distribution incorporates a shape parameter in which the final distribution is the sum of multiple exponential distributions of the same mean. The probability density function of primary screening times ($f_{Y,1}$) for screening service time (y) is parameterized by the mean number of electronic devices carried by passengers (γ) and the primary screening mean service time (μ_1).

$$f_{Y,1}(y, \gamma, \mu_1) = \frac{y^{\gamma-1} e^{-y/\mu_1}}{\mu_1^\gamma (\gamma - 1)!} \tag{2}$$

This is ideal for Bluetooth-monitored security queue modeling as the shape parameter signifies the number of Bluetooth-enabled devices carried by passengers, each of which may commonly require a separate bin and thus additional screening time. The simulation, however, presumed that a single MAC address was chosen to represent each passenger, and was thus conducted with a shape parameter of unity. Note that this simplifies the Erlang distribution to an exponential distribution; a base time (τ) requirement is added to shift the exponential distribution for practical purposes.

$$f_{Y,1}(y, \mu_1, \tau) = 0 \text{ [for } y \leq \tau] f_{Y,1}(y, \mu_1, \tau) = \frac{e^{-(y-\tau)/\mu_1}}{\mu_1} \text{ [for } y > \tau] \tag{3}$$

A truncated Gaussian distribution was assumed for secondary screening due to the degree of variation in secondary selection reasons and screening techniques. The probability density function of secondary screening times ($f_{Y,2}$) for screening service time (y) is parameterized by the secondary screening mean service time (μ_2) and the secondary screening service time standard deviation (σ).

$$f_{Y,2}(y, \mu_2, \sigma) = \frac{e^{-\frac{1}{2} \left(\frac{y-\mu_2}{\sigma} \right)^2}}{\sigma \sqrt{2\pi}} \tag{4}$$

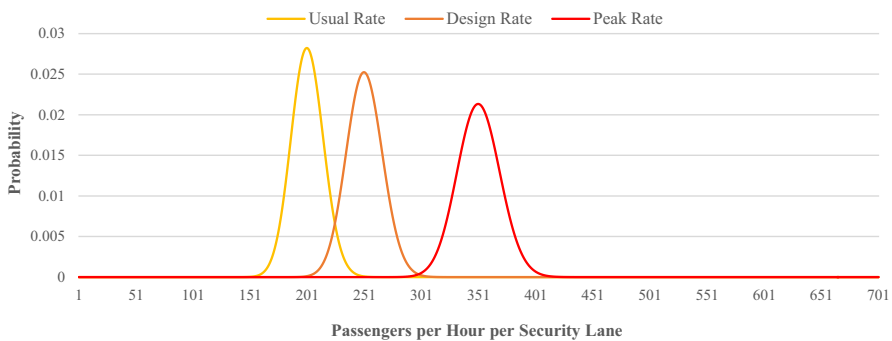


Fig. 2 Probability density functions of passenger entry rates

The simulated primary screening service distribution was a hybrid exponential distribution with a mean of 120 s, adjusted so that the minimum allowable screening time is 60 s (Leone and Das 2010). The secondary screening service distribution was a truncated Gaussian distribution with a mean of 150 s and standard deviation of 15 s (Leone and Das 2010). The distributions are shown in Fig. 3.

Note that the most significant assumption inherent in the above statistical analysis is that adjacent passengers enter and behave independently: passenger entry times and screening times are not dependent upon those of other passengers. In practice, the travel of families or other associates confounds this; however, passengers travelling in groups would choose lanes less efficiently than FCFS as they prioritize staying together over moving quickly, so that simulated FCFS logic is a generous model of actual passenger choices. Another significant limitation in this analysis is the walking time between the point of lane assignment and the end of the lane queue; this is believed to have minimal impact on the application of feedback control due to its presumably small size. Additionally, emergency events in which firearms or similar threats are found in security screenings were not modelled for the sake of simulation simplicity and precision.

Control logic

Various alternative queuing logics, counting FCFS as the evaluation baseline, were compared to find the most promising algorithm for ALAS. These logics included sequential, in which passengers are assigned to lanes in a static and repetitive pattern, random, in which passengers are given lanes via a random number generator, and variants of proportional, integral, or derivative control. FCFS, random (RAND), sequential (SEQ), Proportional (P), Integral (I), Derivative (D), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) assignment controllers were considered, with feedback present for all PID variants.

For control logic requiring feedback of the current states of each screening lane, the following discrete metric of performance relative to the average (x_m) was used as the driving signal given the number of passengers in the screening

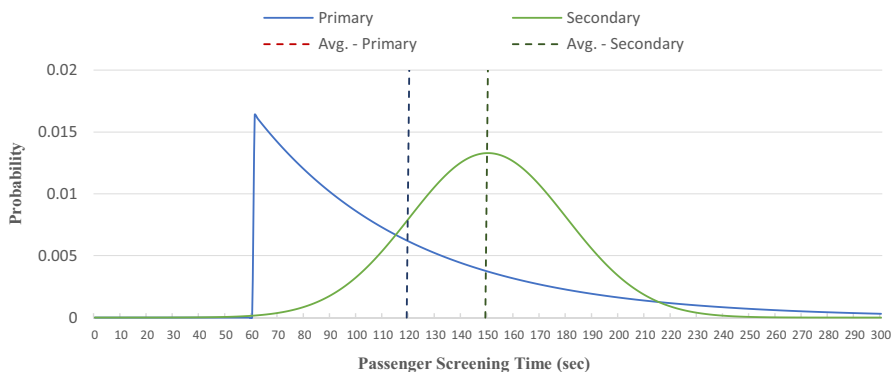


Fig. 3 Probability density functions of passenger screening times

lane (j_m) where m is the screening lane index, and n is the number of screening lanes in the security checkpoint:

$$x_m(t) = j_m(t) - \frac{1}{n} \sum_{m=1}^n j_m(t) \tag{5}$$

Commonly applied to continuous, oscillating systems, proportional, integral, and derivative control are utilized similarly in this discrete-event simulation. Proportional control assigns passengers to lanes based on current queue sizes in a manner quite similar to how passengers are presumed to choose lanes currently. Integral control assigns passengers to lanes based on the accrual of time of all passengers spent waiting in the queue. Derivative control assigns passengers to lanes based on the recent rate of passengers cleared per unit time. The feedback scheme, utilizing PID as the control logic, is depicted in Fig. 4. Where K is the controller gain, and dt the time interval

$$j_m(t + dt) = j_m(t) + \left[K_P(x_m(t)) + K_D\left(\frac{\partial x_m(t)}{\partial t}\right) + K_I\left(\int x_m(t)dt\right) \right] \cdot \frac{1}{n}i(t) \tag{6}$$

Simulation results

Modeling of security screening queues was conducted with the academic version of Rockwell Automation’s Arena Simulation Software. Developed in 2000, Arena is a powerful computational tool in queue management and boasts a popular track record in the aviation industry; airline users include Air Canada and Lufthansa for ticketing and baggage handling while airport users include Dallas-Fort Worth International Airport (Rockwell Automation 2020). An image of the Arena simulation window during a FCFS test of the five-lane, 2-phase SSCP model is shown in Fig. 5. Note that each person icon does not necessarily indicate the presence of only one person in the queueing network.

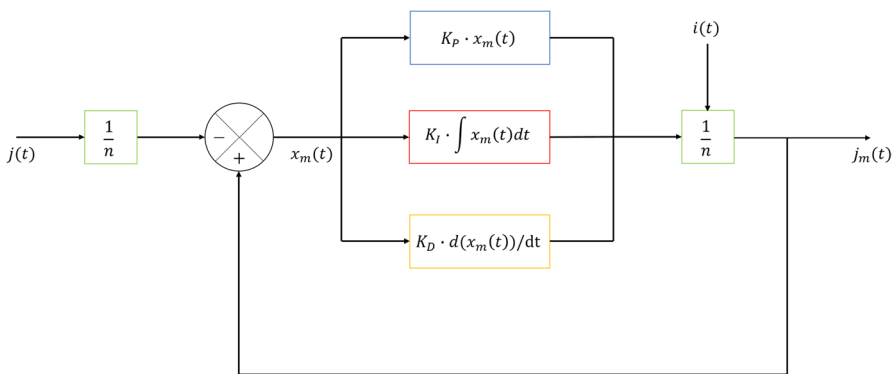


Fig. 4 Schematic of PID control applied to airport security queues

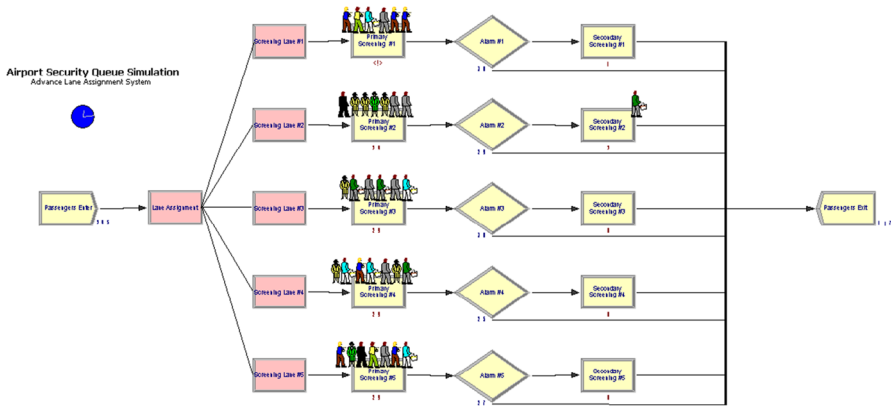


Fig. 5 Arena simulation window of the security screening model

Table 1 Wait time statistics by lane assignment algorithm

Statistic (minutes)	FCFS	RAND	SEQ	P	I	D	PI	PD	PID
Minimum	43.4	50.7	52.0	46.1	42.9	47.2	43.7	45.1	46.6
Maximum	6.3	8.2	8.9	5.6	7.6	4.4	4.8	6.1	5.5
Mean	33.1	37.7	38.2	33.5	32.2	31.0	29.3	31.8	31.3
Median	27.8	36.4	37.9	30.6	25.9	24.2	21.4	22.9	23.7

A total of 100 trials each for nine alternative queuing logics were run under the same simulation scenario: one hour of the usual rate of passenger entries for throughput warm-up, two hours of peak passenger entry rate for stress testing, and one more hour of the usual rate for throughput cool-down. The results of all 900 simulation runs are summarized in Table 1.

Relative to FCFS, Proportional-Integral-Derivative (PID) combined control offers a 12% improvement in mean waiting time and a 23% improvement in median waiting time. Individually, integral control offered the most attractive maximum waiting time while derivative control offered the most attractive minimum waiting time. To describe the statistical significance of these simulation results, a difference of means *t*-test was performed. For observed standard deviations and average waits of FCFS and PID ALAS, as well as equal simulation run sizes of 100, the *t*-statistic was computed to be 2.77. The corresponding two-tailed *t*-test results in a *p*-value of 0.008. At a 95% confidence level, this analysis suggests that PID-equipped ALAS logic offers statistically significant improvements in mean waiting time over the traditional FCFS service discipline in the specific simulation structure.

The simulations described here were verified and validated by assessing the degree to which the inputs and outputs mimic their empirical counterparts. Verification consists of ensuring various input parameters yield reasonable and desirable output results; the better performance of ALAS with PID logic over current FCFS

methodology, as well as common recorded wait times between approximately 5 and 50 min, meets such verification standards. The design rate of passenger entries was also used to check the accuracy of the simulation. This rate was set based on the TSA's ASLs target of 230 passengers per hour per lane and the TSA's delay target of less than 10 min; assuming constant throughput and arrival rates of 230 and 250 passengers per hour per lane for two hours, the 460th to 500th passenger entries would experience the highest waits of between 9.6 and 10.4 min. Tested under the design rate of passenger entry for two hours with FCFS logic, the simulation yielded maximum wait times of 10.8 min, in close accordance with basic analytical estimation. Validation, however, involved a case study of a large checkpoint at a primary commercial airport. EWR's Terminal C was chosen as it often experiences national worsts in security wait times. DHS throughput data for Friday mornings in the month of December 2019 shows an average of 200 passengers were cleared through each of EWR Terminal C's 19 screening lanes; MyTSA wait data shows these peak periods averaged 46 min of waiting (TSA 2020a, b). Tested under the peak rate of passenger entry for two hours under FCFS logic, the simulation yielded an average wait of 43.7 min and per lane throughput of 209 passengers, a 5% difference from the published figures. Note that PreCheck divisions, as well as other EWR Terminals, were neglected in these calculations and may slightly confound this analysis. Such close convergence enhances confidence in the constructed simulation, and consequential displayed performance improvement of PID-equipped ALAS over traditional FCFS.

Impact evaluation

Risk assessment

The overarching risk associated with any facet of transit security is the failure of the general security screening procedure and is of paramount concern. False positives and false negatives (Fig. 6) of screening alarms are both detrimental to the overall security process; in the context of modern terror threats, the threshold of acceptance for false positives is greater than that for false negatives. While wrongly identifying the presence of an illicit item is likely to induce passenger frustration and resource wastage, failing to find potentially harmful objects has far greater implications for aircraft, aircrew, and passenger safety.

Alterations to security procedures are also commonly discussed within the context of a standard risk heat map (Fig. 7). For TSA security breach occurrences, the severity and likelihood of the event depends heavily upon the nature of the prohibited item passing through screening. While the seizing of oversized liquids is a relatively common occurrence resulting from passenger absent-mindedness rather than ill intention, the confiscation of prohibited firearms poses a less frequent but more impactful danger. Due to pressing foreign and domestic threats, the severity of passenger screening failures is deemed moderate to catastrophic; subject to debate given poor performance on recent undercover testing, the frequency of passenger screening failures may be deemed rare to possible (Lardieri 2017). Aggregately,

Fig. 6 Security screening error matrix

		Threat Found	
		Yes	No
Threat Present	Yes	True Positive [No Error]	False Negative [Type II Error]
	No	False Positive [Type I Error]	True Negative [No Error]

airport security is a relatively risky yet essentially tolerable domain such that the development of advanced screening technology and threat countermeasures is a rapidly evolving field.

As ALAS does not alter identification authentication and baggage and body scanning procedures, the risk of security screening failure is, in theory, unchanged. Rather, the core purpose of ALAS is to serve as a protective barrier against the causes and effects of excessive queueing at airport security checkpoints, as shown in Fig. 8. The top event of excessive queueing itself poses several security risks and operational issues, including hazardous congestion of terminal halls, subconscious compromises in security standards, dissatisfaction among air travelers, and

		Severity of Occurrence				
		Negligible [1]	Minor [2]	Moderate [3]	Major [4]	Catastrophic [5]
Chance of Occurrence	Rare [1]	[1]	[2]	[3]	[4]	[5]
	Unlikely [2]	[2]	[4]	[6]	[8]	[10]
	Possible [3]	[3]	[6]	[9]	[12]	[15]
	Likely [4]	[4]	[8]	[12]	[16]	[20]
	Often [5]	[5]	[10]	[15]	[20]	[25]

Fig. 7 Security screening risk matrix

disruptions of flight operations. While minor in severity, the formation of long security lines occurs often and is thus thrust into the caution area of the risk matrix. It is this ever-present risk that ALAS aims to reduce by diminishing the likelihood of formation of such long security queues in the first place.

These potential gains from implementation of the ALAS concept in terms of risk mitigation are weighed against its failure modes and effects. The most probable point of inconsistency in ALAS implementation is failure of the Bluetooth sensing technology. This can occur when passengers disable Bluetooth on their devices, completely power off their devices, or do not travel with Bluetooth-capable devices. However, passengers carrying smart devices of some type remains a relatively reliable assumption given the plethora of modern Bluetooth-capable devices and the presumed socioeconomic status of most air travelers. In developing and testing AWT, it was approximated that 98% of travelers could be identified via the presence of at least one MAC signal (DHS 2012). The likelihood of a large lack of Bluetooth-enabled devices within short time periods that would confound ALAS logic is thus quite rare; similarly, the effects of such a lack of Bluetooth would decline rapidly as more passengers enter the queue to have a near-negligible effect on overall system functionality.

Total ALAS failure, by either hardware, software, or connection fault, may result in degraded performance compared with the simple FCFS service discipline over the short-term. While still remote in likelihood due to high sensor reliability and confidence in assignment logic, ALAS may result in unacceptably long queue lengths. To mitigate the severity of occurrence in such a case, existing line structure techniques, such as wrapping or manual flow control, could be quickly and cheaply instated. In addition, lane selection due to a complete failure of ALAS to produce lane assignments because of a hardware or software fault could devolve to FCFS lane choice. As the chief failure consequence of ALAS is the current baseline method, risk would not be heightened beyond today’s threshold. Inability of ALAS to regulate line length as intended is low in both probability, as components individually are reliable, and severity, as reversion to FCFS would occur, so that risk remains acceptable.

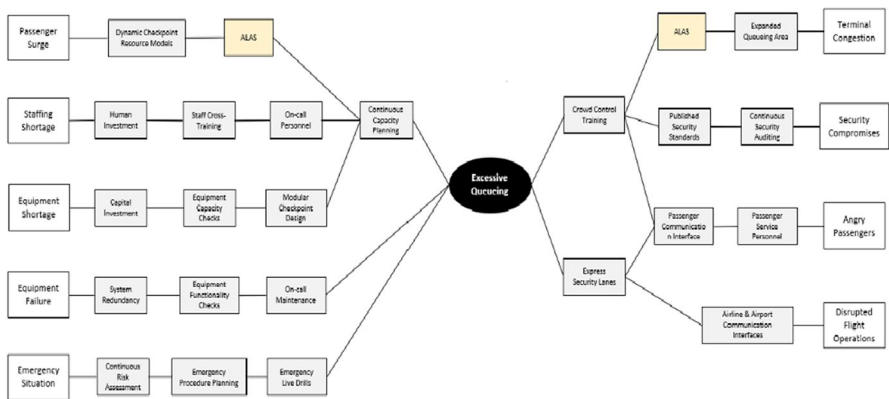


Fig. 8 Airport security queuing causes and effects ‘bowtie’ diagram

By improving queue management technology, ALAS has the potential to improve security screening times by maximizing resource utilization. Security screenings, much like generic industrial processes, may be analyzed as a production function; human and capital resource input levels may be altered, subject to financial and spatial constraints, to drive tradeoffs between process performance parameters.

Security screenings are plotted in Fig. 9 across dimensions of speed and stringency, with a curve representing different full resource allocations and diminishing marginal returns of screening time. Without compromising screening robustness, ALAS aims to shift screenings to the left in Fig. 9 toward a previously unattainable speed for the improvement of passenger and provider experience.

The ALAS concept is believed to have a net positive effect on overall security screening risk. Because it does not alter existing screening technologies and standards, ALAS does not introduce substantial risk to screening robustness and thus passenger safety. ALAS can materially reduce risks due to unsafe terminal congestion, undesired passenger discontent, and subconscious compromises in security rigor that may accompany excessive queueing. The failure modes of ALAS primarily involve those already present with AWT and ensuing technology and would have the relatively small consequence of reversion to current FCFS queue structuring. Altogether, ALAS is believed to be a non-invasive and low-risk method of partially mitigating a commonly frustrating aspect of the passengers' airport experience.

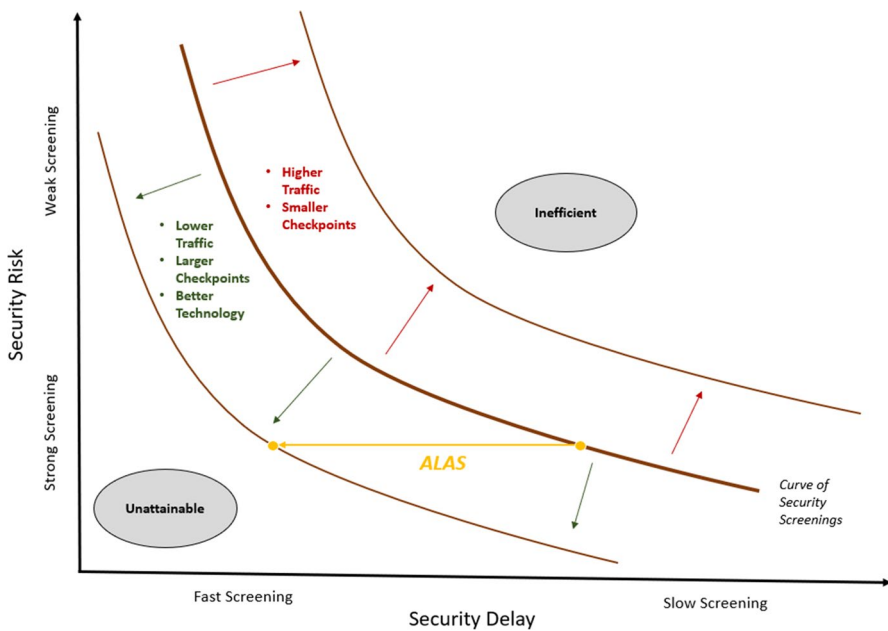


Fig. 9 Airport security screening production possibility frontier

Cost assessment

Airport security systems are accountable to stakeholders of great geographic breadth and structural depth; government divisions most involved include the DHS, Department of Defense, Department of Transportation, and local airport authorities, while corporate entities most affected include airlines and employers of frequent business travelers, and individuals most concerned include commercial air passengers and the general public.

In a general sense, benefits stemming from streamlining airport security queues could be realized for many of these stakeholders. Most important, smoothing passenger flow and evening lane utilization may subtly elevate the rigor of security processes. Apart from safety, the time savings of passengers is both considerable and valuable. Travelers' time can instead be spent in secured terminals, potentially translating to higher vendor sales and lower flight delays for airports and airlines, respectively (Weagle 2019). Specific to the TSA, optimized queueing processes can qualitatively improve public image and quantitatively reduce waiting area congestion much as recent strides in ASL and AWT systems have (Elias 2009). TSA staffing levels and shifting assignments can also be more accurately and dynamically tailored to meet performance goals such as '90–10', in which 90% of passengers experience less than 10 min of security delay, with real-time passenger flow data gleaned from this system.

Though limited by the early stage of system design and testing, quantitative estimations of system financial viability are computed. ALAS development costs are heavily dependent on the expense of developing control software; it is estimated from similar systems that optimized and testable algorithms could be created at an approximate cost of \$1,250,000. Procurement costs are much more well-defined, with high-quality servers for each SSCP costing roughly \$5,000 and proven sensors for each SL costing roughly \$1,000. Expenses of electricity are deemed negligible relative to neighboring scanners; likewise, expenses of customer interfaces that relay lane assignments are assumed negligible as they would be integrated with the rollout of BAT gates or communicated manually by TDCs. Benefits of ALAS are derived from passenger time savings, which are roughly correlated to monetary value by Airlines for America (A4A), an industry trade group, at \$49 per hour per passenger (A4A 2017). For the five-lane SSCP simulation, reduction in mean waiting times by 3.8 min for 1,250 hourly passengers would result in nearly \$3,900 commercial value per peak hour of usage. Within days of operation, these savings could outpace the \$10,000 installment cost for the five-lane SSCP; presuming actual results mirror those simulated, costs are structured as outlined above, and ALAS is most prominent for only two peak hours per day, a prototyping program at a five-lane SSCP would provide monetary time saving benefits equivalent to development and installation costs after approximately half a year of operation. While these figures are promising, however, the lack of maturity of this technology prohibits an accurate, precise, and detailed financial model from being constructed.

Conclusion

As the demand for air travel is expected to return to pre-COVID-19 levels and continue to increase, passengers must be effectively and efficiently moved through the screening process without compromising the robustness of that process. To reduce average

security-induced passenger delays, this paper evaluates an ALAS that directs passenger flow among screening lanes within a checkpoint through timely feedback control. Passengers receive a screening lane assignment at biometric or manual identification authentication gates based on the current performance, namely the lengths, rates, and accruals, of each available screening lane. ALAS involves two primary components: sensor hardware and server software. Bluetooth-tracking sensors, which identify the presence of Bluetooth-enabled devices by recording MAC addresses, are placed at each screening lane to measure passenger flow. Lane assignment logic is then applied to time series data of Bluetooth-enabled devices on a collocated checkpoint server, determining and transmitting optimized lane assignments to ensure equal resource utilizations and decreased waiting times. The system is intentionally designed to synergize and scale with existing TSA infrastructure. Sensor hardware can be provided partially by utilizing those sensors already deployed for AWT estimations, analysis software could be housed on AWT CCS, and assignment communication would most logically occur at automated BAT gates. A five-lane, two-phase model of an airport security screening checkpoint was constructed with statistical distributions of passenger entry and service times; the model was subjected to varying intensities of passenger arrival rates and identical simulations were conducted with alternative lane assignment logic. The control logic and model structure were validated by comparing FCFS simulation results with actual TSA throughput and wait time data and design goals. At a 95% confidence level, PID is shown to be a statistically significant improvement over traditional FCFS in directing passengers to screening lanes under the created queueing model.

Potential impacts of this innovative concept may be realized by a wide variety of commercial aviation stakeholders. By decreasing average wait times without increasing deployed personnel or machinery, the TSA would enjoy reduced queueing area requirements and improved staffing and resource planning models. Likewise, a more streamlined process will reduce passenger waiting time, boost the public image of the TSA and benefit the operations of vendors, airports, and airlines. By autonomously adjusting queue structures, this research aims to fully achieve the operational throughput potential of advanced screening technologies and partially mitigate security-induced delays endured by passengers during peak travel periods. Improving both the effectiveness and efficiency of airport security screenings is an explicit goal of the FAA and TSA and offers substantial benefits across the air transportation industry. As the directive of security screenings is to prevent harm to people and property across the National Airspace System with minimal inconvenience and infringement, ALAS would connect emerging TSA technologies and empower stronger and speedier security processes.

Note that this research was conducted during the declaration of a state of emergency resulting from the coronavirus pandemic. Although the commercial aviation industry was ravaged by the subsequent sudden drop in air travel demand, the provided assessments hold upon the return of normalcy to domestic air transportation, and its continued growth.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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