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Fast and Secure:
Optimizing the airport security queues

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Introduction

In the wake of the tragic events of September 11, 2001, airport security measures have undergone significant enhancements worldwide. These measures aim to prevent potential threats to air travel and ensure the safety of all passengers. However, the challenge lies in striking a delicate balance between maintaining robust security standards and minimizing inconvenience for passengers. Airports seek to optimize passenger throughput, ensuring a positive flying experience, and reducing the time travelers spend in security checkpoints.

The issue of prolonged waiting times at airport security checkpoints gained public attention in 2016, particularly at Chicago's O'Hare International Airport. The Transportation Security Agency (TSA) responded by implementing various modifications to their checkpoint procedures, equipment, and staffing levels. While these changes helped reduce wait times, the associated costs and their effectiveness remain unclear.

Furthermore, there is a perplexing problem of unexplained and unpredictable long lines at various airports, even those known for short wait times. This inconsistency in checkpoint lines can be financially burdensome for passengers deciding between arriving excessively early or risking missing their scheduled flights. This variability in security checkpoint experiences has been a cause for concern, as highlighted in numerous news articles.

To address these challenges, our Internal Control Management (ICM) team has been engaged by the TSA to review the existing security checkpoints and staffing procedures. Our objective is to identify potential bottlenecks that impede passenger throughput and to devise creative solutions that enhance checkpoint efficiency while minimizing the variance in wait times. Our approach seeks to maintain the highest standards of safety and security while simultaneously improving the passenger experience.

The current process at a U.S. airport security checkpoint involves several distinct zones. Passengers initially queue up for identification and document verification in Zone A. Subsequently, in Zone B, passengers prepare their belongings for X-ray screening, pass through scanners or detectors, and undergo additional screening if necessary. Finally, in Zone C, passengers collect their items and exit the checkpoint area.

Approximately 45% of passengers are enrolled in the Pre-Check program, which offers expedited screening for trusted travelers. These travelers undergo a similar screening process but with specific modifications designed to expedite their journey.

Problem

The problem at hand pertains to the optimization of passenger throughput at airport security checkpoints while maintaining stringent security standards and minimizing passenger inconvenience. Airport security measures have evolved significantly since the events of September 11, 2001, with the primary objectives of preventing hijackings, ensuring the safety of passengers, and securing air travel. However, the challenge is to strike a delicate balance between robust security and a positive passenger experience.

The primary issues that the TSA wishes to be researched and potentially solved are as follows:

1. Tracking the flow of passengers: Developing a model that allows the TSA to track the flow of passengers through a security checkpoint to identify bottlenecks.
2. High Variability in Security Checkpoints: The high variance in wait times at different airports, including those with a history of short wait times, raises concerns about the effectiveness of security procedures and passenger throughput.
3. Cultural and Behavioral Factors: Cultural norms and traveler behaviors can significantly impact how passengers process through security checkpoints. It is crucial to consider these factors when proposing solutions to improve passenger throughput and reduce wait time variances.
4. Policies and Recommendations: Based on our research; the TSA hopes to obtain policy recommendations that could be globally applicable or may be tailored to most cultures and traveler types.

Given:

In this section, we aim to highlight some of the assumptions and data that have been provided to us by the TSA

1. The problem involves optimizing the passenger throughput at an airport security checkpoint, with a focus on reducing waiting times while maintaining security standards.
2. The U.S. Transportation Security Agency (TSA) has experienced criticism for long security checkpoint lines, and various modifications have been made to address this issue.
3. The current process involves several zones, including Zone A for initial document checks, Zone B for X-ray screening and passenger processing, and Zone C for collecting belongings.
4. Approximately 45% of passengers enroll in the Pre-Check program, which offers expedited screening with fewer requirements, such as not removing shoes and belts.
5. The TSA also provided the data with various columns each column has the following meaning.
    a. TSA PreCheck Arrival Times - Airport checkpoint recording individuals entering the pre-check queue.
    b. Regular Arrival Times - Airport checkpoint recording individuals entering the regular queue
    c. ID check TSA officers 1 & 2 - The time of arrival of a passenger to the ID check station until the TSA officer calls the next passenger forward.
    d. MM wave scan times - Time stamps as passenger exited the millimeter wave scanner
    e. X-Ray Scan Time 1 & 2 - Time stamps as bags exited the x-ray screening
    f. Time to get scanned property - The time it takes people from arriving at the belt to place items to be scanned until they retrieve their items off the post-x-ray belt.
6. The table below shows the summary statistics (mean, min, max, and column length) of the data that was provided by the TSA. To obtain the summary the sequential time series data was

converted to obtain the difference between each recoded value giving us the time between each recording.

Column Names	Mean (in Seconds)	Min (in Seconds)	Max (in Seconds)	Data Provided (in Seconds)
TSA Pre-Check Arrival	9.189474	0.47	34.72	57.0
Regular Pax Arrival Times	12.945870	0.52	78.89	46.0
ID check Prcoess Time 1	1.27	0.33	2.83	8.0
ID check Process Time 2	2.158333	0.13	5.67	6.0
Millimeter Wave Scan Times	11.637179	3.50	37.44	39.0
X-Ray Scan Time 1	7.542	1.69	25.91	10.0
X-Ray Scan Time 2	3.67	1.53	7.55	3.0
Time to Get Scanned Property	28.620690	5.00	68.00	29.0

Table 1: Basic Summary of the Data provided by the TSA

7. The general visual layout of the airport security was also provided by the TSA.

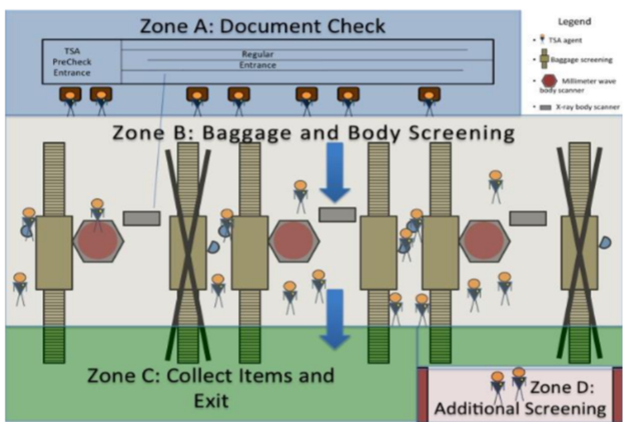

Figure 1: This image shows the layout of the current security checkpoint at the airport where the data was recorded.

Assumptions

Some of the assumptions we can make before developing our model:

1. Each queue is independent of another.
2. We are assuming a standard Fist-in-first-out (FIFO) queue. The dynamics of a queue can change drastically if other types of queue systems are used.

3. No Jockeying, Balking, or Reneging. In other words, if a passenger joins a queue they remain in the queue for the whole duration.
4. We are going to assume that the queue is largely infinite meaning that there is a constant stream of passengers arriving at the security checkpoint throughout the day.
5. The values provided by the TSA are accurate and a good representation of the overall queue times.
6. The data follows an exponential or Markovian distribution. We are using the Markovian distribution to capture a high variability of our data to account for varying passengers with different cultural backgrounds traveling through the airport.
7. There are about seven ID check stations and two queues for the ID document check (based on image 1)
8. There are about three millimeter scan points and four baggage x-ray points that were open when the data was recorded. With a possible increase in the x-ray checks. Our simulation would be using three checkpoints. (based on image 1)
9. TSA Pre-check Arrival = Accounts for about 57 passengers in 8 minutes (Based on the data provided there are a total of 57 passengers that pass through the checkpoint within an 8-minute duration) which is equivalent to about 7 passengers per minute or 0.1167 people per second. However, TSA pre-check arrival does not account for passengers who are part of the pre-check program and can avoid the main queue.
10. Regular Pax Arrival Times = Pax arrival times are similar to the pre-check arrival times; however, pax times are recorded when the passengers join the regular queue. We can perform similar calculations as we did for the pre-check arrival times to ascertain that roughly 5 people are arriving at the airport per minute. Which then equates to 0.2 minutes between each passenger. We will hence assume that λ (mean arrival time) is 0.2 passengers per minute. (Gosavi)
11. ID check queue 1: Provides us with the meantime of each passenger waiting in the queue (W_q or mean passenger wait time in queue). We are going to add an assumption that the first queue

connects to four of the seven ID document check stations (Based on image 1). Since the mean wait time seems to be lower compared to the second queue.

12. ID check queue 2: Also provides us with the meantime of each passenger waiting in the second queue (W_q). We will assume that the second queue leads to the other three ID document check stations (Based on image 1). (Gosavi)
13. Millimeter wave scan times: Since this value records the times at which the passengers leave we assume that the difference between those records is equal to the amount of time a passenger spent in the queue before the scan (W_q). We will additionally assume that the service time for the wave scan includes the time a passenger took to remove their personal belongings and place their belonging on the belt before proceeding to the millimeter scan. (Gosavi)
14. X-ray scan times: Similar to millimeter wave scan times, the x-ray times contain entries of the bags leaving the scanner. We will once again assume that the values are equivalent to the average wait time a bag spent in the scan queue (W_q). Since the number of data entries provided from X-ray scan 2 is three (Based on Table 1), we will be combining X-ray scans 1 and 2. However, by combining the two features we are further assuming that the W_q values and service time values are approximately the same for both queues. We will additionally assume that the service time for the x-ray scan includes the time a passenger took to remove their personal belongings and place their belonging on the belt. (Gosavi)

Model Development and Results

Based on our assumptions and since most queues contain multiple service stations we will be utilizing the M/M/s queuing model to identify service times since those times are not provided. We will additionally be breaking the problem down into each designated column provided to calculate the average service time if $\lambda = 0.2$ minutes per passenger (In Assumptions). We can additionally convert all our mean values in Table 1 to minutes to maintain a consistent value for any further calculations. (Bhat -2)

M/M/s Model:

Since we are provided the λ and W_q we can use some of the M/M/s (The Kendel notation denotes that the probability distribution of the interarrival time and the probability distribution of the service time follows a Markovian distribution (M) and there are s number of servers in the system) model equations to derive the μ (Mean service time). We can use the given values to first calculate the L_q. (Bhat -2)

$$W_q = L_q / \lambda$$

Equation 1: Shows that the wait time can be divided by the mean number of customers in the queue (L_q) by the mean arrival rate (λ)

Once we calculate L_q we can then use a formula that is used to calculate L_q to calculate the value of μ. (Bhat -2)

$$L_q = [\frac{1}{(s-1)!} * (\frac{\lambda}{\mu})^s * \frac{\lambda\mu}{(s\mu-\lambda)^2}] * P_o$$

Equation 2: Shows the formula used to calculate the L_q. where s is equal to the number of servers available and P_o is the probability that there are no customers in the system (Bhat -2)

However, we would also need to find the P_o value which is given by the formula:

$$P_o = [\sum_{n=0}^{s-1} \frac{1}{n!} (\frac{\lambda}{\mu})^n + \frac{1}{s!} * (\frac{\lambda}{\mu})^s * \frac{s\mu}{s\mu-\lambda}]^{-1}$$

Equation 3: Provides the formula that is used to calculate the P_o value.(Bhat -2)

If we combine the P_o formula with our formula for L_q we get the following:

$$L_q = [\frac{1}{(s-1)!} * (\frac{\lambda}{\mu})^s * \frac{\lambda\mu}{(s\mu-\lambda)^2}][\sum_{n=0}^{s-1} \frac{1}{n!} (\frac{\lambda}{\mu})^n + \frac{1}{s!} * (\frac{\lambda}{\mu})^s * \frac{s\mu}{s\mu-\lambda}]^{-1}$$

Equation 4: P_o in Equation 2 was substituted by the formula in Equation 3

We can then place our known values for the first queue in the ID check process with 4 servers (s = 4) and solve for μ. The example of what the formula looks like once the values are provided is as follows.

Where L_q was calculated as 0.1050 from L_q = 1.27/60 * 0.2 = 0.0042

(Note: W_q was converted into minutes from seconds such that the values match $\lambda = 0.2$ people per minute.)

$$0.0042 = [\frac{1}{(4-1)!} * (\frac{0.2}{\mu})^s * \frac{0.2\mu}{(4\mu - 0.2)^2}][\sum_{n=0}^{4-1} \frac{1}{n!} (\frac{0.2}{\mu})^n + \frac{1}{4!} * (\frac{0.2}{\mu})^4 * \frac{4\mu}{4\mu - 0.2}]^{-1}$$

Equation 5: Shows the example of what the substituted values look like. Given Equation 4

We can now solve for μ and obtain the mean service time. Which happens to be 0.2217 minutes per person. Using this formula we can now calculate the μ for our other ID queue. The table below shows the values that were calculated based on the L_q and W_q values provided.

	λ	s	W_q	L_q	μ
ID check Queue 1	0.2 min/pass	4 Servers	0.211 mins	0.0042 pass	0.2217 mins/pass
ID check Queue 2	0.2 min/pass	3 Servers	0.0360 mins	0.0072 pass	0.3203 mins/pass

Table 2: Shows the values that were obtained after using Equation 4 for the average time of service for each customer (μ) for the ID check queues

M/M/1 Model:

Since our data provided suggests that each the initial two queues result in various singular queue. We can now employ the use of a single queue. Fortunately, the formula used to calculate the L_q from W_q is still the same. Hence using equation 1 we can calculate L_q. However, to calculate μ we must use a different formula. The formula is given below: (Bhat -1)

$$L_q = \frac{(\frac{\lambda}{\mu})^2}{1 - \frac{\lambda}{\mu}}$$

Equation 6: The following formula shows how we can calculate for mu if the values of L_q and λ are known. (Bhat -1)

Using Equation 6 we can now calculate the remaining service time values for the millimeter scan as well as the baggage x-ray scan.

	λ	s	W_q	L_q	μ
Millimeter Wave Scan	0.2 min/pass	1 Server	0.1940 mins	0.0388 pass	1.12 mins/pass
X-ray Baggage Scan	0.2 min/pass	1 Server	0.11 mins	0.02 pass	1.51 mins/pass

Table 3: Shows the values obtained after using Equation 6 for the average time of service for each customer (μ) for Millimeter-wave scan and X-ray baggage Scan

The μ values seem rather high. However, based on our assumptions regarding the millimeter wave scan and the x-ray baggage scan these values seem adequate. (see assumptions)

Inferences and Further Calculations:

We can make some basic inferences from our calculations. The load factor or the average time each server, counter, millimeter wave scanner, or baggage x-ray screening was busy. We can calculate this using the following formula:

$$\rho = \frac{\lambda}{s\mu}$$

Equation 7: shows the formula for calculating the utilization factor (ρ) of each server. (Bhat -2)

Using this formula for all our queues we can obtain the following plot:

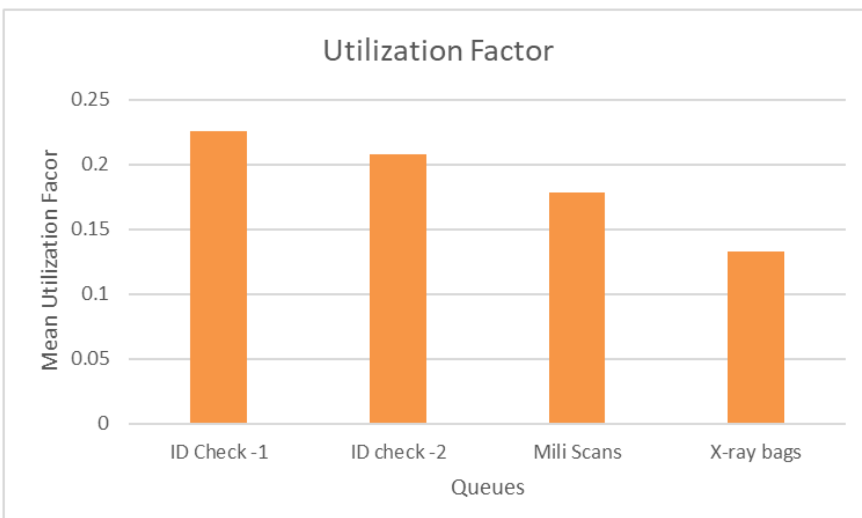

Figure 2: We can note that from our calculations the average utilization of each server is largely around 0.2.

Looking at the utilization score one may think that we may need to increase our utilization of each server to reduce the wait times and improve performance. However, in terms of queues, a high utilization factor is generally not ideal There is a clear tradeoff between wait times and utilization factors. (John) If the utilization of the server increases the wait time would also increase. Additionally, since we are assuming a Markovian distribution for our queues, the wait time would increase exponentially as shown in the image below.

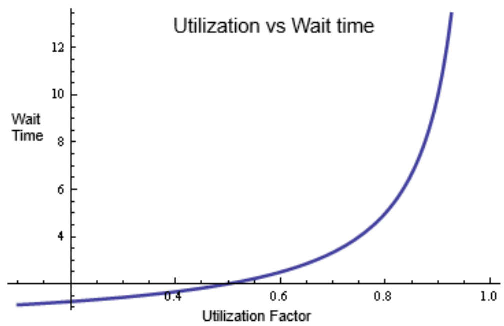

Figure 3: The figure shows the inverse relationship between utilization factor and wait time. We can observe that generally, the best utilization factor is around 0.5 if we still wish to keep the wait times low. (John)

Based on Figure 3 we can hence determine that the best utilization factor to be around 0.5. Looking back at the values in Figure 2 we can note that our utilization factor could be improved upon across all queues. Since a low utilization rate suggests a high idle time for the servers in the queue. Perhaps decreasing the number of queues in this scenario provided by the TSA would provide a more efficient system with a slight increase in the wait times.

Moreover, since we were provided with the mean time it takes for a bag to be scanned (Time to get Scanned Property (See Given)) we can now determine the mean time it takes for a person and their belongings in the queue to arrive at the belt and place their bags and metal objects they may on their person by simply subtracting the scan time with the service time that we determined for the bags. Hence, the $\mu_{\text{X-ray scan}}$ - Mean time to get scanned property (1.51 mins(Table 3) - 0.477 mins (Table 1)) equals 1.03 mins. Suggesting that on average it takes a person about a minute to fully rid their person of metal objects or bags.

Additionally, we can now subtract the amount of time it takes a person to place their items to be scanned by the total service time for the millimeter scan to obtain the time it takes a person on average to go through the millimeter scanner. Which is about 0.09 minutes or just about 5 seconds (1.12 mins (Table 3) - 1.03 mins).

Simulation

We created a basic simulation with about 100 passengers and simulated the queue 1000 times. The data was generated using an exponential distribution (see assumptions) based upon our data that was generated from the λ and μ. The reason the simulation was run several times was to simulate the variability in our data as much as possible. After running the simulation the following results were obtained.

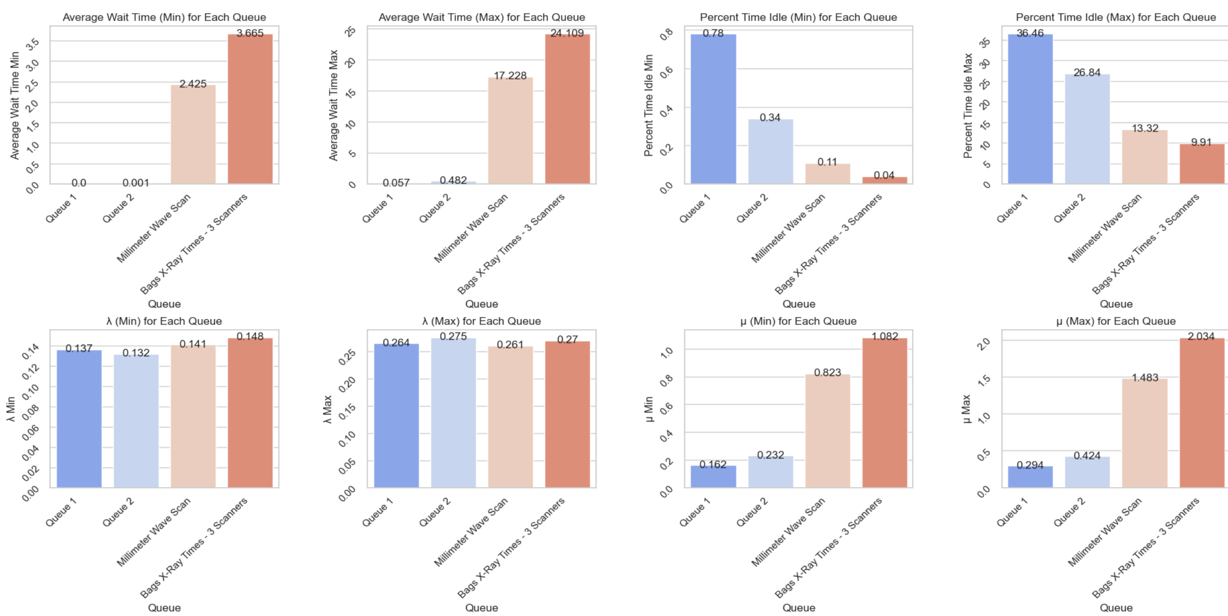

Figure 3: Performance Metrics for Queues

The queues represent various aspects of the system, including ID check, Millimeter Wave scan, and Bags X-ray.

Queue 1, equipped with 4 servers, has an average arrival rate (λ) of approximately 0.200157 customers per unit of time, and the average service rate (μ) is around 0.221321. This leads to an average wait time of just 0.002049, indicating minimal customer waiting in this queue. The percent of the time that the servers are idle stands at 9.64% suggesting efficient utilization.

Queue 2 with 3 servers, shows similar performance trends. The arrival rate (λ) is about 0.200201, while the service rate (μ) is approximately 0.319654. The average wait time is slightly higher at 0.058165, yet still relatively low, and the servers have an idle time percentage of 5.96%

The Millimeter Wave Scan Queue, also equipped with 3 servers, exhibits some contrasting characteristics. The arrival rate (λ) is similar to the previous queues at 0.200708, but the service rate (μ) is notably higher at 1.130627. This leads to a substantially longer average wait time of 8.485601, with only 3.07% idle time, possibly indicating a bottleneck in the process.

The Bag X-ray system, which employs three scanners, reveals distinctive performance metrics. The arrival rate (λ) is approximately 0.200101, akin to previous queues, while the service rate (μ) stands notably higher at 1.503315. Consequently, this results in an extended average wait time of 14.287565, indicating a relatively longer processing time for bags in the queue. Moreover, the percent time idle, at 2.325640, suggests that the system remains fairly active, with only 2.09% of idle time. This combination of higher service rate and relatively low idle time indicates efficient but potentially resource-intensive operations, possibly requiring optimization to reduce waiting times and enhance overall system efficiency.

We can observe that since we assumed exponential distribution we can have varying values which means that in worst cases at certain checkpoints, an individual may have to wait a significant amount of time further showcasing our calculations and providing a much-needed perspective of the numbers we calculated in the previous sections. We can also clearly observe that the wait times at Zone B can be a real bottleneck. Some of the possible solutions and thoughts on the data we gathered from the simulation as well as our calculations will be outlined in the next section.

Discussion

Based on the data provided by the Transportation Security Administration (TSA), we have determined the service times for various queues at the airport security checkpoints. Our findings indicate that the mean service time for the initial identification (ID) checkpoint in Zone A is approximately 0.2217 minutes per passenger or roughly 13.302 seconds. Similarly, the second checkpoint queue in Zone A has a service time of 0.3203 minutes, equivalent to 19.21 seconds per passenger. Notably, it is evident that the time required for passengers to complete the document identification process is relatively short, implying that the bottleneck likely occurs in the subsequent area, specifically Zone B.

Within Zone B, we have obtained service times for both the millimeter-wave scanner and the X-ray scanner for passengers' bags and belongings. According to our model, the service time for the millimeter-wave scan is estimated at 1.12 minutes or 1 minute and 7 seconds per passenger. This value may appear high, but it encompasses the time it takes for passengers to remove their belongings, place them on the X-ray queue, and walk to the millimeter-wave scanner. Similarly, the service time for a passenger's bag is approximately 1.51 minutes or 1 minute and 31 seconds, which also includes the time it takes for a passenger to place the bag in the X-ray queue. It is important to note that these times may seem extended due to the comprehensive nature of the service time calculations.

Moreover, we have calculated the utilization factor, which indicates how effectively the queues are being used concerning passenger arrivals. Our analysis shows that the utilization rate for all the queues is consistently below 0.2, suggesting that a slight increase in utilization through a reduction in queues, particularly for the ID checks, may not significantly impact overall wait times. However, such adjustments could enhance the efficiency of the checkpoints and reduce the risk of long idle durations.

Furthermore, we have deduced that passengers typically take an average of approximately 1 minute to remove their belongings before undergoing the millimeter-wave scan. Subsequently, the time required for a passenger to pass through the millimeter scan after placing their bags on the belt is roughly 5 seconds. This duration aligns closely with the estimate provided by the National Laboratory of the Pacific Northwest, which suggests that the scan itself takes approximately 1-2 seconds (PNNL).

To gain deeper insights, we have conducted simulations of the queues using the service rates obtained from our model. The simulations are based on an exponential distribution, providing valuable perspectives on wait times and the impact of variations in service times and passenger arrival rates on queue lengths. According to our simulations, the maximum wait time for queues in Zone B could extend to 24 minutes for the X-ray scans and around 17 minutes for the Millimeter scan. Based on these findings, we recommend that the airport focuses on reducing the variance in service times to mitigate the risk of excessively long queues.

In summary, our results highlight that the bottleneck and prolonged wait times primarily occur in Zone B. Consequently, implementing a pre-check program may not yield significant improvements, especially if service times remain relatively consistent and it takes an average of one minute for passengers to remove items and prepare for the checkpoint process. Additionally, our simulations account for variances in passenger arrivals and service times, allowing us to model various types of travelers, including those from diverse cultural backgrounds.

One policy recommendation we propose is the implementation of measures to encourage passengers to remove metallic objects and prepare to a certain extent before reaching the checkpoint. This would serve to reduce overall wait times, as the time required for passengers to remove personal items would be minimized.

Sensitivity Analysis

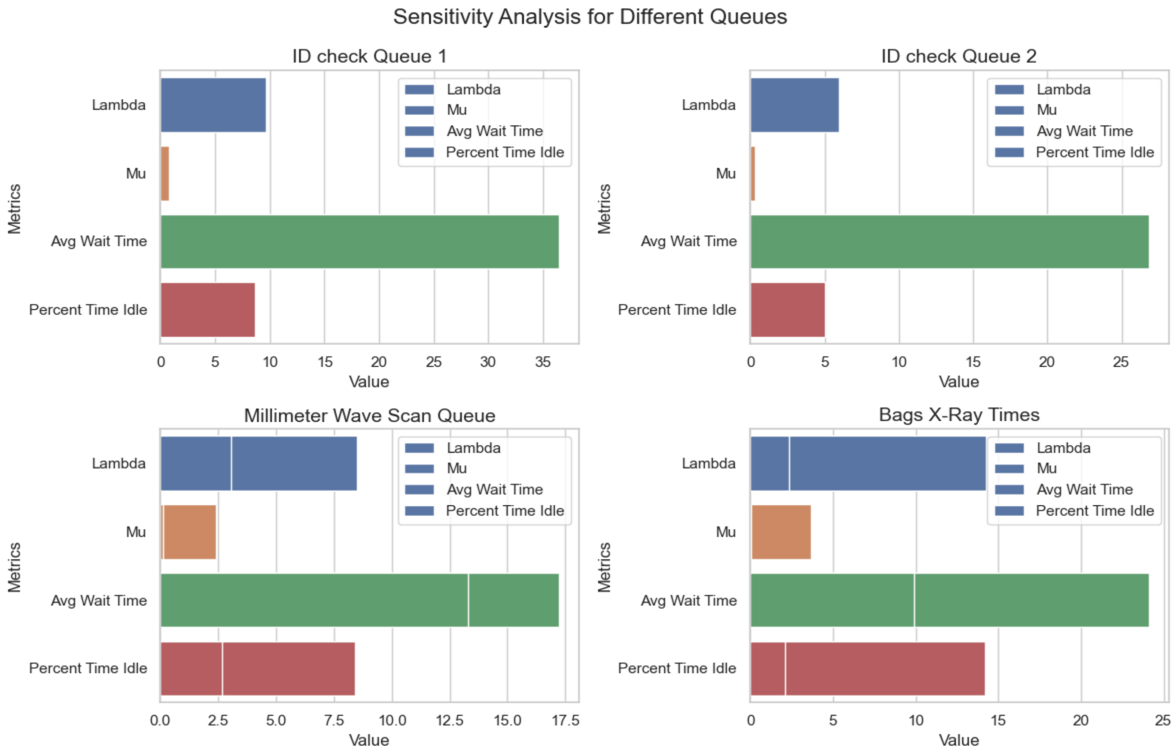

Figure 4: Sensitivity Analysis for Different Queues

In the realm of airport security, maintaining safety standards while enhancing passenger throughput is a paramount challenge. The provided sensitivity analysis offers a comprehensive examination of key metrics for different queues at the airport security checkpoint. These metrics, including λ (arrival rate), μ (service rate), W_q (Average Wait Time), and Percent Time Idle, play a pivotal role in understanding and optimizing the efficiency of the security checkpoint.

- <u>ID Check Queue 1</u>: This queue exhibits moderate arrival and service rates, resulting in an average wait time of just 0.002049 minutes. Notably, approximately 9.64% of the time, the ID check stations remain idle, suggesting that a fine-tuned resource allocation strategy could enhance efficiency.

- <u>ID Check Queue 2</u>: In contrast, ID Check Queue 2 shows a similar arrival rate to Queue 1 but features a higher service rate. This results in a significantly higher average wait time of 0.058165 minutes. The Percent Time Idle is around 5.96%, implying that resources may need to be adjusted to reduce waiting times.
- <u>Millimeter Wave Scan Queue</u>: This queue exhibits relatively balanced arrival and service rates. The average wait time, however, spikes to 8.485601 minutes, with a Percent Time Idle of approximately 3.07%. The significant wait times warrant a close examination of resource allocation and process optimization.
- <u>Bags X-Ray Times</u>: With a high arrival rate and relatively low service rate, the Bags X-Ray Queue experiences the longest average wait time, standing at 14.287565 minutes. Despite a Percent Time Idle of around 2.33%, substantial room for improvement is evident.

In the presented sensitivity analysis, each queue's metrics are scrutinized to identify areas where efficiency enhancements can be made. The evaluation of Lambda and Mu rates, together with Average Wait Times and Percent Time Idle, unveils the specific challenges and opportunities for optimization. To enhance airport security checkpoint efficiency, it is crucial to consider resource allocation, staffing, and process improvements. The sensitivity analysis provides a robust foundation for informed decision-making. Implementing appropriate adjustments, such as allocating additional resources to high-wait queues or streamlining processes, can minimize wait times, reduce idle periods, and improve overall passenger throughput.

In conclusion, the sensitivity analysis reveals the dynamic nature of passenger queues at airport security checkpoints and offers actionable insights for refining operational strategies. Balancing security measures with passenger convenience is an ongoing challenge, and this analysis serves as a valuable tool for making data-driven decisions to optimize the traveler experience while ensuring safety.

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