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AN APPLICATION OF RELIABILITY ANALYSIS TO TAXI-OUT DELAY: THE CASE OF NEW YORK JOHN F. KENNEDY INTERNATIONAL AIRPORT

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ABSTRACT

Improving the efficiency of ground surface movement is a key preoccupation of airline and airport operators. As taxi-out times increase, take-off queues are likely to grow and impact the on-time arrivals and departures at a specific airport and beyond. This article utilizes reliability analysis to identify the mean time to taxi-out delay as an indicator of imbalance between capacity and demand to prevent delays. The study shows that taxiway improvements and virtual queue departure management contributed to reduce the meantime to taxi-out delay from 18.53 in 2007 to 8.11 minutes in 2011.

INTRODUCTION

Taxi-out delay represents the difference between actual taxi-out time and a nominal or unimpeded taxi-out time. In this article, taxi-out time is measured from the moment an aircraft leaves the gate until the time it takes off. The source of taxi-out data is ARINC[1]'s Out-Off-On-In (OOOI) data compiled by the Bureau of Transportation Statistics[2] (BTS) and available in the Federal Aviation Administration's Aviation System Performance Metrics[3] (ASPM). ASPM reports unimpeded taxi-out times based on the domestic air carriers reporting in the monthly Airline Service Quality Performance (ASQP) survey. Unimpeded taxi-out time represents the time that it takes for a taxiing aircraft to go from gate to takeoff when there is only one aircraft ahead in the take-off queue.

This study is based on the case of New York John F. Kennedy International Airport. It uses monthly data for calendar year 2007—when delays were at an all-time high—and calendar 2011—after several initiatives such as virtual departure queue management and taxiway redesign had been implemented to improve ground surface movements. Based on ASPM data, the average taxi-out time declined from 35.76 minutes in 2007 to 25.98 minutes in 2011, while, in the same time comparison, taxi-out delays went down from 18.94 to 8.5 minutes. Since international operations at JFK represented 68.38% and 64.31% of the total operations respectively in 2007 and 2011[4], ASPM instead of ASQP metrics were selected because the former embrace scheduled domestic and international carriers. It is also important to mention that the Official Airline Guide (OAG) and Innovata reported a decline in the total number of scheduled operations by 6.79% in 2011 compared with 2007 when the number of take-offs and landings reached 429,739.

Both taxi-out time and delay are important operational metrics because long taxi-out times and delays create an imbalance between insufficient airport capacity and high air carriers' demand for arrivals and departures. Longer taxi-out times and taxi-out delays are two variables likely to cause longer block times (gate-to-gate times) and airport congestion, a situation that often compels air traffic control to stop operations as part of traffic management initiatives in order to re-establish a balance between capacity and demand. As aircraft move slower along the taxiways, the demand for departure increases while take-off queues are likely to grow. When an airport cannot meet increased departure demand, departing flights are either delayed or even cancelled. Recent regulations have provided an incentive for airlines to reduce excessive taxi times: They can face fines of up to $27,500 per passenger when a plane sits on the tarmac for more than two hours without providing food or water or more than three hours without giving passengers the option of getting off the plane[4].

Identifying the point of trade-off between capacity and demand is important for airport and airline analysts. The former needs to manage gate availability and airport services, while the latter is often involved in evaluating potential obstacles to on-time performance. Improving ground surface movement efficiency is one of the key objectives for the Next Generation of Air Transportation called NextGen. The 'Improved Surface Movement' portfolio—including operational increments such as the 'Initial Surface Traffic Management'—targets departures sequencing and staging to maintain throughput. According to the NextGen Implementation Plan, the automation and integration of surface movement operations with departure sequencing is designed to ensure that aircraft meet departure schedule times while optimizing the physical queue in the movement area.

The balance between capacity and demand is all the more significant at peak times or in the case of adverse weather. Since delay is the trade-off between demand and available capacity, reliability analysis can help analysts identify the 'mean time to failure' and the 'failure rate' in the form of maximum sustainable taxi-out delay that sets off airport congestion. The methodology explained in this paper enables aviation analysts and practitioners to identify extreme taxi-out delay. Reliability analysis and extreme value analysis have been mainly used in structural engineering, finance, geological engineering, among others. However, it has not been applied to the study of delay and congestion. The study will start with an explanation of the methodology; proceed with the model outputs and interpretation before concluding with some remarks.

METHODOLOGY

The Weibull distribution can be used to estimate the reliability or probability of taxi-out delay as well as the mean time of taxi-out delay. The RELIABILITY procedure in SAS was used to perform Weibull analysis. The Weibull probability density function of a random variable x is characterized as

$$F(x; \lambda, \kappa) = \kappa/\lambda(x/\lambda)^{\kappa-1}e^{-(x/\lambda)\kappa} \quad x \geq 0 \quad (1)$$
$$= 0 \qquad\qquad x \leq 0 \quad (2)$$

where k > 0 is the shape parameter and λ > 0 is the scale parameter of the distribution. The Weibull failure rate is computed as follows:

$$h(x; \lambda, \kappa) = \kappa/\lambda(x/\lambda)^{\kappa-1} \quad (3)$$

The constant λ is called the scale parameter, because it scales the x variable, and the constant ⬚ is called the shape parameter, because it determines the shape of the rate function. If ⬚ in greater than 1 the rate increases with x, whereas if ⬚ is less than 1 the rate decreases with x. The Weibull distribution is very flexible. If ⬚ = 1, then the rate is constant, in which case the Weibull distribution equals the exponential distribution. If ⬚ = 2, the Weibull distribution is close to the Raleigh distribution. When ⬚ ≈ 3.5, the Weibull distribution approximates the normal distribution.

The hazard function is the ratio of the probability density function to the survival function. It is sometimes referred to as the conditional failure density function in reliability analysis. The hazard function of the Weibull distribution is

$$h(x) = \kappa(x)^{\kappa-1} \quad x \geq 0 \quad \text{and } \kappa > 0 \quad (4)$$

The monthly taxi-out delays for calendar year 2007 and 2011 were converted into estimated reliability values using the median rank method. The latter estimates the delay values based on an order of magnitude and the cumulative binomial distribution. According to Dodson (2006: 19), "the median rank is a non-parametric estimate of the cumulative distribution function based on ordered failures." The delay values are ordered from the lowest to the highest and the median ranks are computed by applying the following formula:

$$\text{Median Rank} = (\text{Taxi-Out Delay} - 0.3)/(n + 0.4) \quad (5)$$

While the Gumbel and Frechet distribution both apply to the largest extreme values, the Weibull distribution is often used to relate to the smallest extreme value. According to Dodson (2006:14), "the type III asymptotic distribution for the minima is simply the Weibull distribution. The type I asymptotic distribution for maxima and minima, also known as Extreme Value Distribution (EVD), is closely related to the Weibull distribution". The EVD reliability function can be expressed as

$$R(x) = \exp[-\exp(x - \lambda/\kappa)] \quad (6)$$

Model Outputs and Interpretation

The hazard plots show the observed taxi-out delays while the line represents the predicted value from the model. In Figure 1 and 2, the natural logarithm of the cumulative hazard function (Y-axis) is plotted against the natural logarithm of taxi-out delay (X-axis) and a straight line is fit to the data. The slope of the line represents the shape parameter κ. The hazard plots are usually used as a measure of goodness of fit[7]. "A straight line of the plotted points indicates that the chosen density function is acceptable" (Dodson, 2006:19). The goodness of fit can be measured by the coefficient of determination R^2: It was .82 for CY 2007 and .95 for CY 2011.

Table 1 provides the survival probability estimates for the Weibull distribution with the stated shape and characteristic life parameters. It is the probability that taxi-out delay will reach a specific number of minutes given the shape (κ) and scale (λ) of the distribution. The reliability probability represents the inverse of the survival probability. The gamma function was used to determine the mean and variance of the Weibull distribution[8].

Since κ > 1, the rate of taxi-out delays is increasing. In 2007, the mean taxi-out delay was 18.53 minutes with a variance of 1.16 minutes. In 2011, the mean taxi-out delay was 8.11 minutes with a variance of 6.44 minutes. The Weibull characteristic life called λ measures the scale, or spread, in the distribution of data. Based on the Weibull distribution parameters, 99% of the departures in 2007 would have at least 27 minutes of taxi-out delay compared with at least 14 minutes in 2011, almost a 50% decline[9]. In 2007, 50% of the departures would have a taxi-out delay of 18.53 minutes compared with 8.11 minutes in 2011.

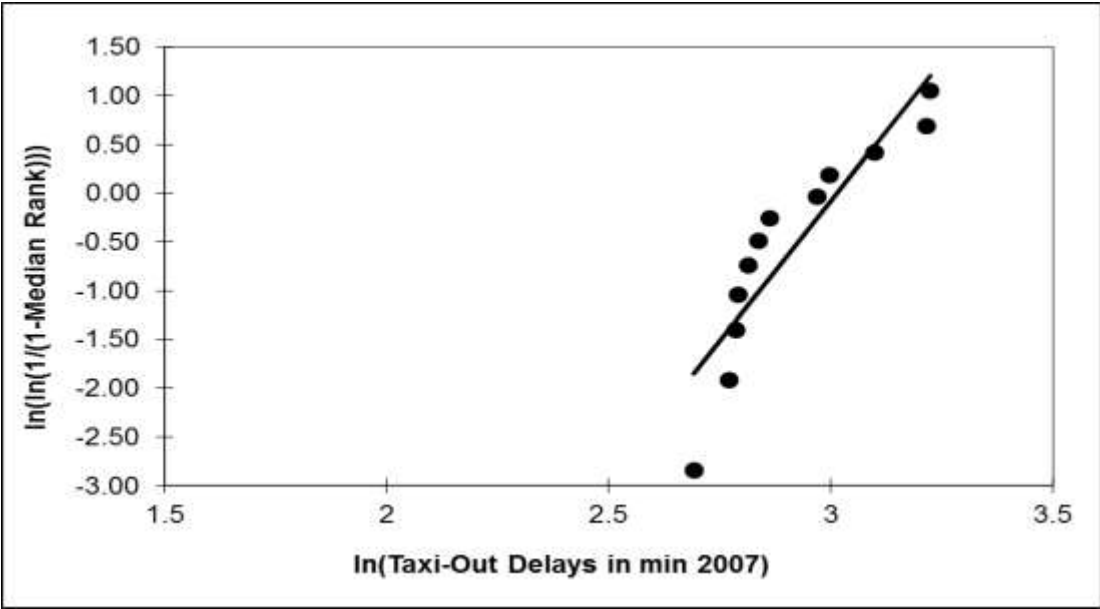**Figure 1: Weibull Hazard Plot (JFK, CY 2007)**
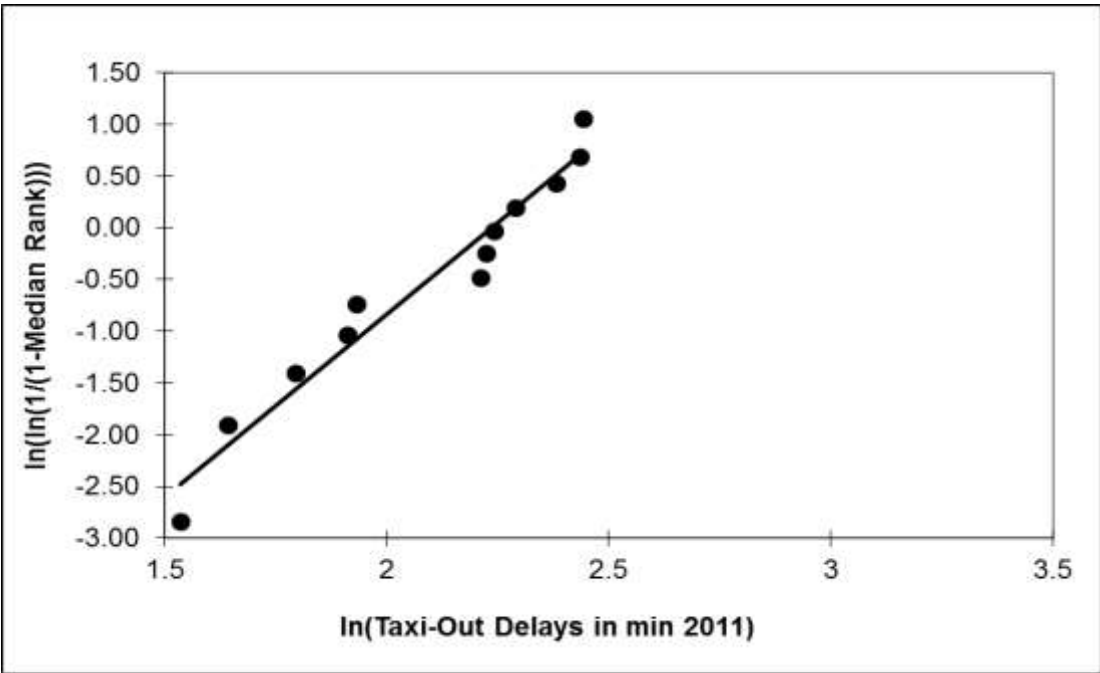

Figure 2: Weibull Hazard Plot (JFK, CY 2011)

Table 1: Survival Probability and Reliability (Taxi-Out Delay in Minutes)

Taxi-Out Delay (min)	Calendar Year 2007		Calendar Year 2011	
	Survival Probability	Reliability	Survival Probability	Reliability
5	.0003	.9997	.1174	.8826
10	.0167	.9833	.7659	.2341
15	.1589	.8411	.9978	.0022
20	.5952	.4048	1.0000	.0000
25	.9617	.0383	1.0000	.0000
30	.9999	.0001	1.0000	.0000

Mean Taxi-Out Delay	**18.53**	**8.11**
Variance	**1.16**	**6.44**
Kappa (Shape Parameter)	**5.75**	**3.54**
Lambda (Characteristic Life)	**20**	**9**

Figure 4 shows the survival probabilities of taxi-out delay. The formula for the Weibull survival function is as follows:

$$S(x) = \exp-(x^\kappa) \text{ (7) with } x \geq 0 \text{ and } \kappa > 0 \text{ (7)}$$

Figure 4: JFK: Taxi-Out Delay Survival Graph
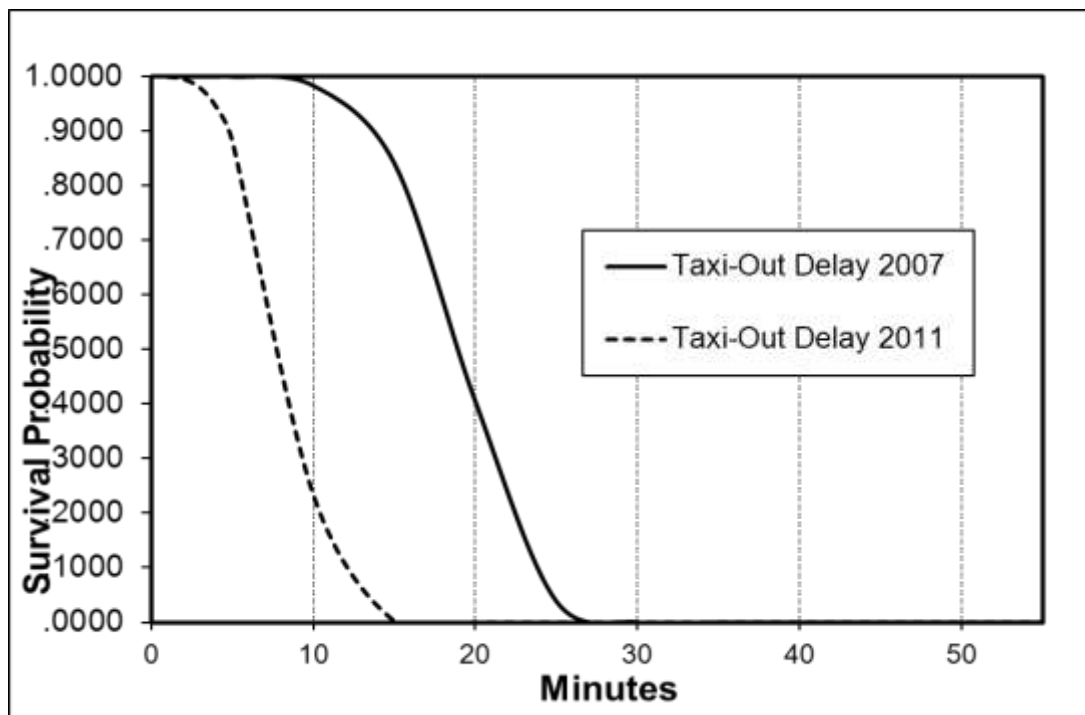
Based on the sampled data, a regression model can be used to identify the percent of capacity utilized as a function of taxi-out delay and number of departure. As an example, for 2011, the regression model can be expressed as follows:

$$Y_{2011} = 23.92 + 0.68* \text{Taxi-out delay} + 0.58*\text{Departures} \ (R^2 = 0.88) \ (8)$$

t value: 4.11   3.60   4.17

p-value: 0.002 0.005   0.002

Therefore, with 27 minutes of taxi-out delays and 45 departures, the expected percent of capacity utilized would be 68.38%.

CONCLUDING COMMENTS

Taxi-out delay is a key measure of airport efficiency and its variation is likely to affect the balance between available capacity and demand. Weibull analysis can help airport and airline analysts identify the minima of the extreme value distribution.

The survival curves show improvements in taxi-out delay, which can be attributed to ground surface movement management initiatives. To improve airport congestion, the New York/New Jersey Port Authority worked with the Federal Aviation Administration to establish a virtual queue system. The purpose of such an initiative was to release an aircraft from its gate when conditions are such that it will not be impeded by ramp congestion and will not wait in a takeoff queue prior to takeoff. NextGen's surface movement capabilities (listed under the Improved Surface Operations of the Implementation Plan) are designed to reduce taxi-out times and delays by providing more information to the pilots prior to take off, improving departure routing and revising pilot departure clearance through the use of DataComm.

REFERENCES

Dodson, B. (2006). The Weibull Analysis Handbook. American Society for Quality, Quality Press.

Federal Aviation Administration. (2012). NextGen Implementation Plan: http://www.faa.gov/nextgen/implementation/plan.

Weibull, W. (1951). "A statistical distribution function of wide applicability", Journal of Applied Mechanics-Transactions ASME 18 (3): 293–297.

NOTES

1. Aeronautical Radio, Inc. (http://www.airinc.com).

2. Bureau of Transportation Statistics (http://www.bts.gov).

3. Aviation System Performance Metrics (https://aspm.faa.gov).

4. The information is based on the Official Airline Guide (http://www.oag.com) and Innovata flight schedules (http://www.innovata-llc.com).

5. Part 14 of the Code of Federal Regulation (CFR) 259.4 addresses lengthy tarmac delays.

6. The 2012 NextGen Implementation Plan is available at the following site: http://www.faa.gov/nextgen/implementation/media/NextGen_Implementation_Plan_2012.pdf.

7. Other methods to test the goodness of fit include the Hollander-Proschan test that compares the reliability function to the Kaplan-Meier estimate of the reliability function, as well as the Mann-Scheuer-Fertig and the Anderson-Darling tests.

8. The mean is computed as $\mu = \delta + \lambda*\Gamma(1 + 1/\kappa)$ and the variance as $\sigma^2 = \lambda^2[\Gamma(1 + 2/\kappa) - \Gamma^2(1 + 1/\kappa)]$, with δ (the location parameter) being zero in this study.

9. If the reliability level is 0.01 and based on the derived Weibull distribution, the estimated taxi-out delay in 2011 in 99% of the departures would be computed as follows: $R = \lambda*(-\ln(x))^{(1/\kappa)} = 9 * (-\ln(0.01))^{(1/3.54)} = 14$ minutes.