

# NASA LOW VISIBILITY LANDING AND SURFACE OPERATIONS (LVLASO) RUNWAY OCCUPANCY TIME (ROT) ANALYSIS

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## Abstract

Runway occupancy time (ROT) data are essential to effectively monitor current airport operating efficiencies and to plan for the introduction of new aircraft surface movement guidance and control systems. This study was commissioned to provide a large and useful set of current ROT data for a major airport that could be used to support analyses aimed at improving the efficiency and safety of surface operations. This study was conducted at Atlanta's Hartsfield International Airport using the NASA Dynamic Runway Occupancy Measurement System (DROMS). Analyses were conducted to determine the factors that determine ROT such as aircraft weight, velocity, air carrier, and meteorological conditions.

## Introduction

This report presents the analysis of runway occupancy times (ROT) for aircraft landing at Atlanta Hartsfield International Airport [1]. ROT data provide metrics on a critical aircraft operating parameter that is a significant driver for overall National Airspace System (NAS) operation. ROT provides a baseline measurement of current operations against which to measure improvements or degradations caused by changing procedures or introducing new technologies. The DROMS allowed the automated collection of a large number of aircraft movements over a 15-day period. During the 15-day period the system provided ROT for over 3000 landings, and each ROT sample included aircraft type, operator, runway and exit used. Weather data, including

rainfall, wind speed, and wind direction, were collected and correlated with the ROT data.

## Data Overview

For fifteen days, during the period 10/1/97 to 11/4/97, data were collected on aircraft surface movements on the north side of Atlanta Hartsfield International Airport (Figure 1). The surveillance system was used to identify aircraft by their transmitted Mode S address and, using multilateration, each aircraft's position was calculated approximately once per second. The accuracy of the surveillance system for the north side of Atlanta is estimated to be  $\pm 15.8$  meters (95%) [2]. From the aircraft's time-tagged position, it was possible to determine the entrance and exit locations and event times. During this period the surveillance system recorded 3326 aircraft landings and surface movements - approximately 221 per day. DROMS data were sorted by runway, exit used, weight class (large, heavy or small), approach speed category (A, B, C, D) and runway conditions (dry, wet, etc.).

## Data Used

Data included aircraft landing on all four runways on the airport's north side (8L, 8R, 26L, 26R). The number of samples for each runway can be seen in Table 1.

**Table 1. Observations Used For The Analysis**

Runway	Total Number of Observations	Number of Observations Used for Analysis
26R	701	595
26L	34	0
8R	268	235
8L	2816	2454
total	3819	3284



**Figure 1. North side of Atlanta Hartsfield**

The samples for 26L were considered insufficient for meaningful analysis. Other data samples were excluded from the analysis for several reasons:

- ROTs below 25 seconds and above 65 seconds were deleted. Those less than 25 seconds were assumed to be incorrect, and those above 65 seconds were assumed to be taxiing to specific points at the far end of the runway.
- After removing outliers, the data set included only 17 small aircraft samples. These were considered insufficient for any type of analysis.
- 368 samples of unknown aircraft type were deleted.

## Analysis

The data probability density function (PDF) was analyzed and concluded to be normally distributed. The PDF data was compared to known distribution PDFs. A curve fitting technique minimizing the difference in area between two curves was used to select the closest match. From all 3282 data points, the ROT for all runways and aircraft has a mean of 44.13 seconds and a standard deviation of 7.46 seconds.

### *Aircraft Classification and ROT*

For aviation studies, it is usual to group aircraft according to a weight or speed category. In this analysis, both groupings are used. Normally, weight categories might be considered sufficient. But for an analysis of time on the runway, categorization by both aircraft speed and weight did prove to be more useful. In addition, data were classified based

on air carrier to determine any relationship with ROT.

### Weight Classification

Data were grouped into three standard aircraft weight classes: heavy, large, and small, as shown in Table 2. The weight is the maximum gross landing weight allowed for a specific aircraft model.

**Table 2. Weight Classifications Used for Atlanta Data Set**

Heavy	Large	Small
> 255,000 lbs	41,000 lbs - 255,00 lbs	< 41,000 lbs
707, 747, 757*, 767	727, 737	B200, FALCON 50
A300, A310	MD80, MD88	BAE JETSTREAM 3201
DC8, DC10	A320, G2, G3	BE20, BE55, DA50
L-1011	ATR 72, DC9, F28	
MD-11	BAE 146, CL60	

\*The B757 has been placed in the Heavy category to match wake vortex in-trail spacing requirements.

As stated above, the data set for small aircraft was considered insufficient for evaluation—the aircraft types are shown here only for completeness. The ROT statistical analysis shows that the heavy aircraft have a mean ROT of 47.55 seconds, which is approximately 4 seconds longer than the ROT for large aircraft at 43.02 seconds. These values were shown to be different to a 0.005 level of significance (see next section and Table 3). The correlation coefficient between weight and ROT is 0.81.

### Speed Classification

In defining the criteria for approach, aircraft are classified by approach category. The approach categories are based on the speed of the aircraft during landing. The speed for particular aircraft are based on 1.3 times the stall speed (at maximum gross landing weight). The categories are listed as follows:

- Category A is below 91 kts.
- Category B is between 91 and 120 kts.
- Category C is between 121 and 140 kts.
- Category D is between 141 and 165 kts.
- Category E is above 165 kts.

The data collected for this study included aircraft only in categories B, C, and D. The mean ROT for speed categories B, C, and D were 38.92, 43.85, and 52.22 seconds respectively. Table 3 shows that mean ROTs for the various speed and weight classes are different to a level of significance of 0.005. These were determined using a student's t-test (one-tailed). It can also be seen in Table 3 that for all cases, the computed test statistic (t) greatly exceeds the minimum required (2.58) to reject the null hypothesis, which implies that the mean ROTs are equal.

**Table 3. Statistical Test Results of ROT Differences Between Speed and Weight Classes**

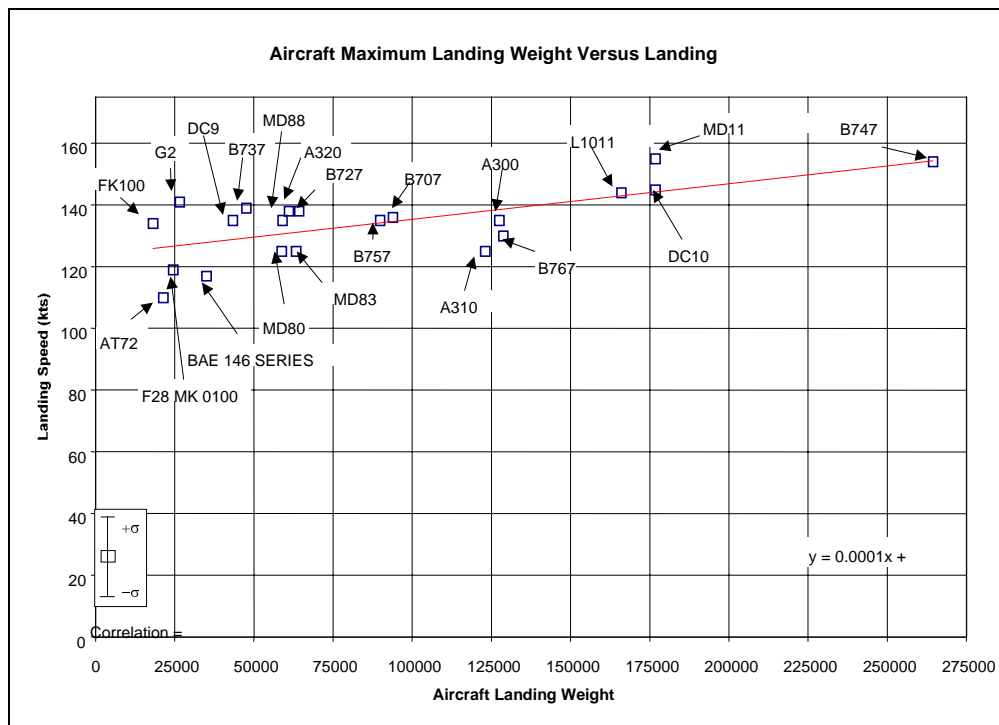
	Weight Categories Large & Heavy	Speed Categories B & C	Speed Categories C & D	Speed Categories B & D
Computed t	15.53	8.46	15.73	12.47
t (0.005)	2.58	2.58	2.58	2.58

The effects of landing air speed on mean ROT based on aircraft type shows conclusively that speed and ROT are highly correlated, with a correlation coefficient of 0.77.

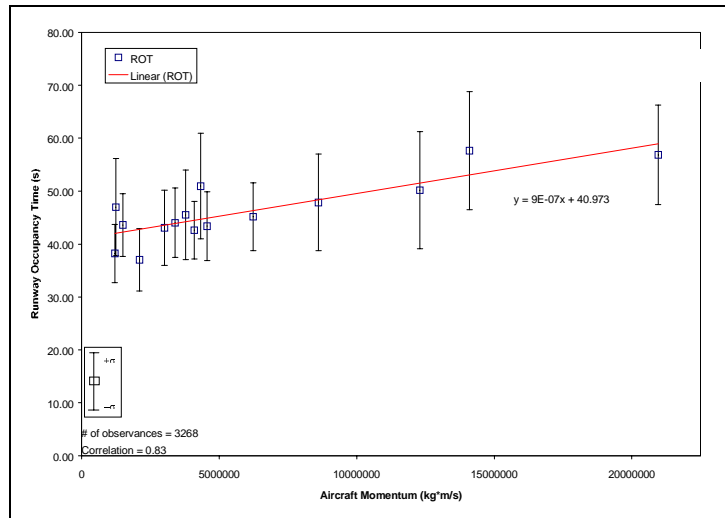
**Combined Weight and Speed**

As the weight of an aircraft increases, the trend is for the aircraft landing speed to increase as well. This is not always the case when each aircraft type is considered individually as demonstrated by Figure 2. Overall though, there is a high correlation (r=0.67) between weight and landing speed.

The rate of deceleration following touchdown is a function of the braking force and the momentum of the aircraft. Momentum is a function of speed and mass. Figure 3 shows the relationship between momentum (mass x speed) and ROT. As already shown, ROT is directly correlated with speed and mass individually. Since momentum is the product of speed and mass, it is logical for ROT to be also highly correlated with momentum. Figure 3 shows just that, with a correlation coefficient of 0.83.



**Figure 2. Relationship Between Weight and Landing Speed**



**Figure 3. Effects of Combined Weight and Speed (Momentum) on ROT**

### Carrier Classification

An analysis was performed to determine if individual carriers displayed any tendencies for longer or shorter ROT. The carriers selected for the analyses were based on the number of observations available. All aircraft for a given carrier were grouped and there was no significant variation in ROT for any one carrier. Among five carriers tested, the largest difference in mean ROT was approximately 3 seconds. To eliminate the errors caused by the wide variety of aircraft types, the analysis was narrowed to include aircraft only in speed category C. These results were similar to the results for all aircraft, with a maximum difference in mean ROT of 3.6 seconds.

Similar analyses were performed on runways 8R and 26R. They displayed the same behavior as 8L. The results indicate that for this data set, there were no individual carriers that were motivated to exit quicker or slower than any other carrier.

### *Effects of environmental and operational conditions*

During the data collection period the weather was clear and VFR. There was some rainfall recorded allowing a comparison between operations on wet and dry runways.

### Effects of Headwinds/Tailwinds

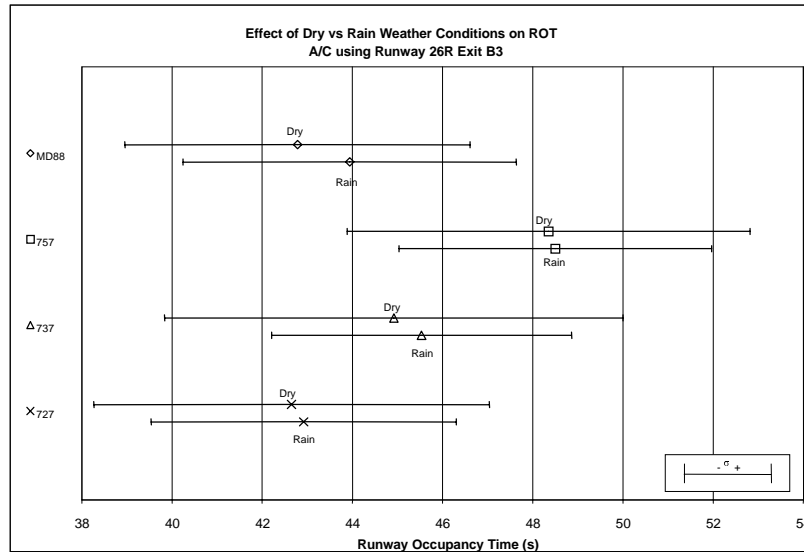
Wind speed was calculated where data was available and the effect of the head wind component on ROT was studied. The results appear to show no overall direct correlation between wind speed and ROT. However, by analyzing the effect of wind speed on individual aircraft types it was observed that wind speed does effect ROT for individual aircraft types in different manners. For example, the ROT for the MD 88 increases as head wind increases. Conversely, ROT decreases with an increasing head wind for the DC 9. However, no general conclusions from this data set were drawn regarding the effects of head or tail winds.

### Dry/Wet Runways

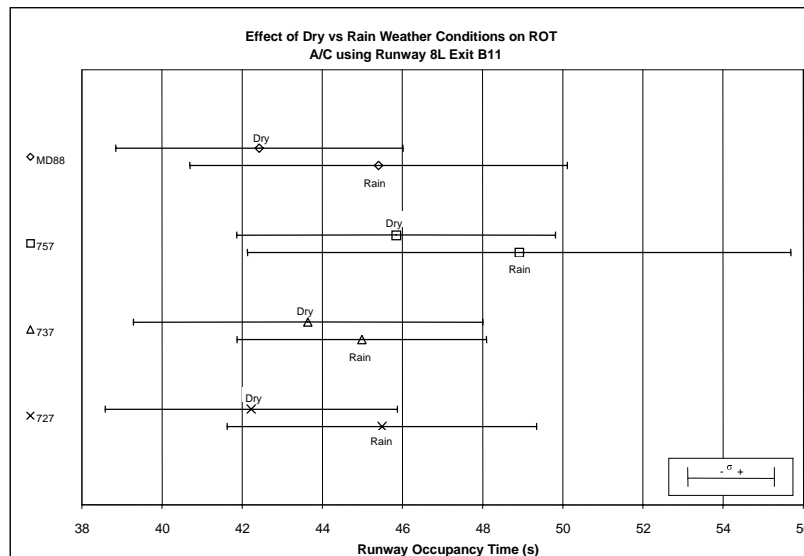
Wet runway conditions displayed a mean ROT of 46.66 seconds where dry runway ROT was 43.91 seconds. Although small, the difference is statistically significant. The initial analysis was performed for all aircraft using all runways and all exits. This data showed a difference between dry and wet weather conditions of approximately 3 seconds. Further analysis was performed to look at the effect of ROT on a single aircraft using a single runway exit zone. Table 4 shows the results of this analysis and Figures 4 and 5 plot these results for runway 26R exit B3 and runway 8L exit B11, respectively. Both of these are high-speed exits.

**Table 4. Effects of Rain on ROT for a Single Aircraft Using a Single Exit**

Aircraft	Runway/Exit	Weather	$\mu$	$\sigma$	Observations
MD88	26R/B3	Dry	42.78	3.83	116
		Rain	43.94	3.69	28
	8L/B11	Dry	42.43	3.58	562
		Rain	45.40	4.71	27
757	26R/B3	Dry	48.35	4.47	50
		Rain	48.50	3.47	12
	8L/B11	Dry	45.84	3.97	225
		Rain	48.91	6.78	13
737	26R/B3	Dry	44.92	5.08	41
		Rain	45.54	3.33	5
	8L/B11	Dry	43.64	4.36	158
		Rain	44.99	3.11	12
727	26R/B3	Dry	42.65	4.39	87
		Rain	42.92	3.38	14
	8L/B11	Dry	42.23	3.64	401
		Rain	45.49	3.86	26



**Figure 4. Effect of Rain for Aircraft Using Runway 26R Exit B3**



**Figure 5. Effect of Rain for Aircraft Using Runway 8L Exit B11**

These results show that runway 8L exit B11 is affected by rain conditions more than runway 26R exit B3. This analysis did not take into account the extended period of deceleration due to a wet runway. The extended deceleration may force an aircraft to take a later exit. A better analysis is to include all exits and sort the data by weight and speed categories. Table 5 shows the results from this analysis.

**Table 5. Effect of Rain on ROT for Weight and Speed Categories Using All Exits**

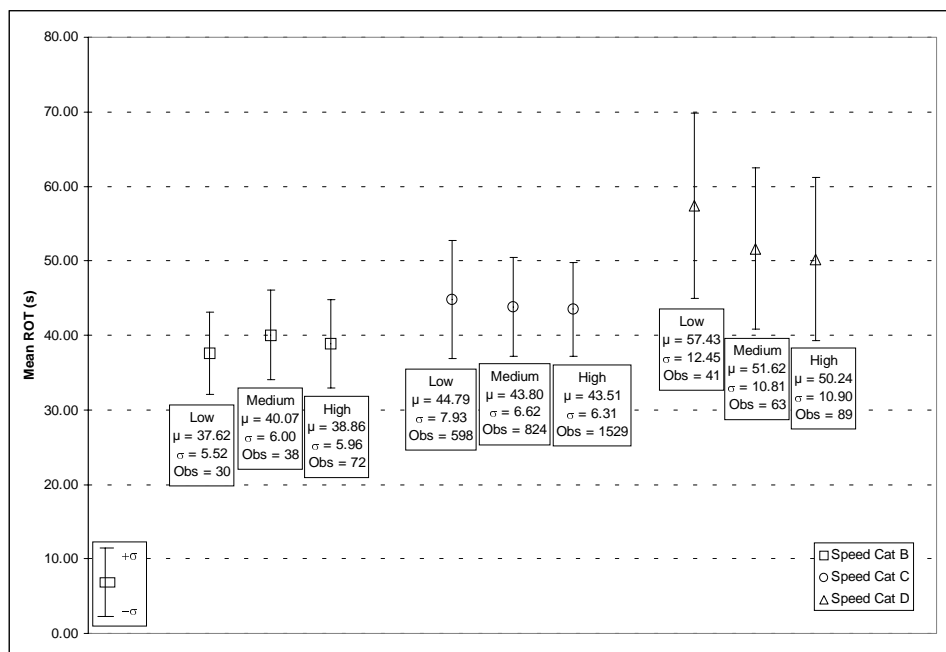
Category	Mean ROT (s)		Difference in Mean (s)	Level of significance
	Dry	Rain		
Large	42.79	45.74	2.94	0.063
Heavy	47.40	49.07	1.67	0.001
B	38.63	42.74	4.11	0.018
C	43.65	46.22	2.58	0.001
D	51.94	55.08	3.13	0.144

These results show that ROT does increase when the runway is wet for all aircraft classifications. This increase is less than 5% of the dry ROT. A z-test with a significance level of 0.0005 was performed to validate this hypothesis, which yielded a statistical z of 1.147 and a critical z of 3.291. Since the statistical value is less than the critical value,

the hypothesis that the difference is less than 5% is true. It should be noted that one limitation of this analysis was that the exact condition of the runway, particularly braking conditions, was not known. The only information available was whether or not it was raining at the time.

### Traffic Conditions

The DROMS data provided traffic density information. The level of traffic was rated as being low, medium, or high. The analysis of this data shows that for aircraft in speed category D, as the traffic density increases, the amount of ROT decreases. This relationship is not as clear for aircraft in speed category C and is not even present in speed category B. These results can be seen in Figure 6. When all aircraft are pooled and analyzed together, the data shows a slight decrease of approximately one second in the mean ROT between low and medium density, and the same decrease between medium and high. In addition to the effect on the mean ROT, the standard deviation tends to decrease as the traffic density increases. These results are shown in Figure 7.



**Figure 6. Effect of Traffic Density on ROT for Speed Categories B, C, and D**

### Day/Night Conditions

The DROMS data includes time of day data, indicating whether the observation occurred at night or during the day. The analysis of this data indicated that there is a significant difference in ROT, where ROT is larger at night than during the day. The level of significance is shown in Table 6. Differences

in ROT for speed categories B, C, and D are shown in Figure 8. A combined analysis for all aircraft showed a daytime mean ROT of 43.75 seconds and 47.13 for night. The same behavior identified in the individual aircraft speed categories exists when the data is pooled for all aircraft.

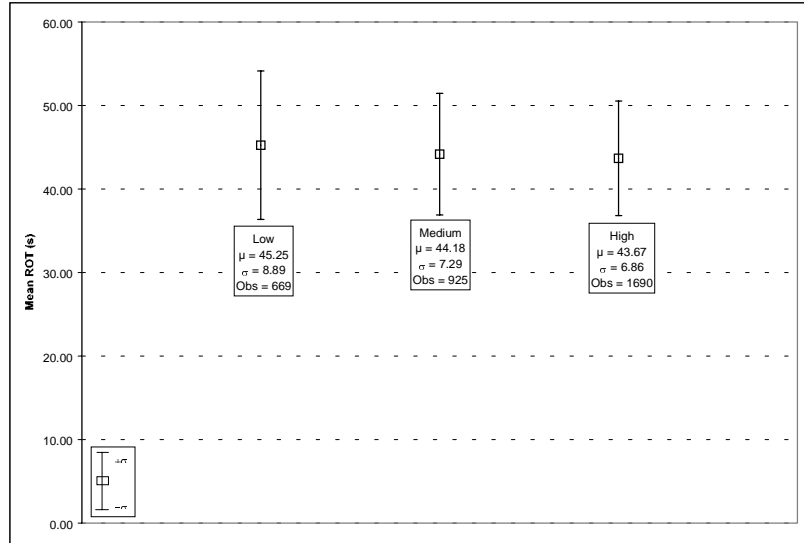


Figure 7. Effect of Traffic Density on ROT for All Aircraft

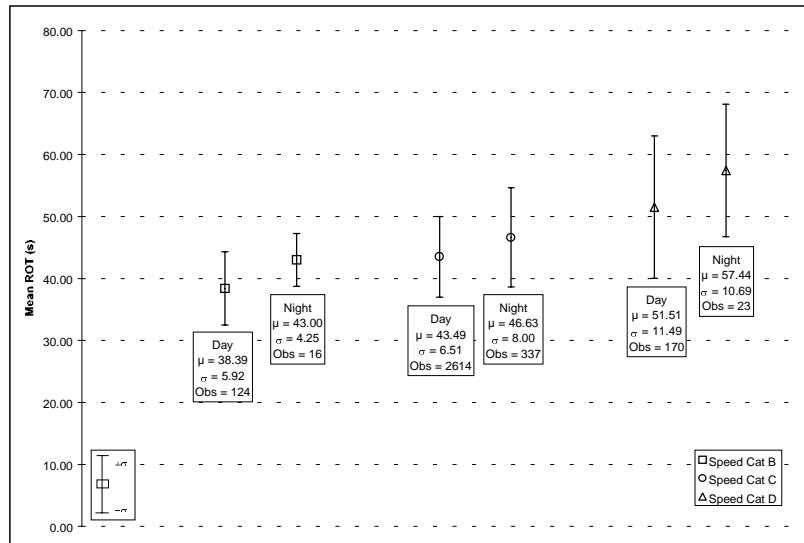


Figure 8. Effect of Time of Day on ROT for Speed Categories B, C, and D

Table 6. Effect of Time of Day on ROT

Speed Category	Mean ROT (s)		Difference in mean	Standard Deviation (s)		Level of significance
	Day	Night		Day	Night	
B	38.4	43.0	4.6	5.9	4.3	0.001
C	43.5	46.6	3.1	6.5	8.0	0.001
D	51.5	57.4	5.9	11.5	10.7	0.011
ALL	43.7	47.1	3.4	7.2	8.5	0.001

## Results Discussion

Previous analyses have suggested that ROT can be reduced by motivating pilots and airlines to exit runways sooner (Ref [3]). From the results presented in this analysis, there were no observed differences in ROTs for the various carriers operating out of ATL. It could be that none of these carriers are "motivated" to reduce ROT, or that ATC procedures in Atlanta somehow restrict individual operators in this regard. Carriers in Atlanta include American, Delta, Northwest, United.

## Conclusions & Recommendations

There are a number of significant conclusions that can be made based on the analysis documented in this paper. They are:

- ROT is dependent on both aircraft speed and weight. There was roughly equal correlation between speed, weight and momentum (speed times weight). This probably indicates that momentum is the primary dependent variable, and that since speed and weight contribute equally to that, ROT is equally dependent on both factors. Some previous analyses have assumed ROT is dependent on aircraft weight, which is true but an oversimplification, especially when grouped according to just the three weight categories.
- No significant differences in ROT were observed between different carriers or operators. There were several carriers in Atlanta with sufficient sample sizes to compare to the ROT observed.
- ROT increases by a small amount in wet runway conditions. For similar aircraft types and runway exits, the data set showed an overall increase in ROT of less than 5% in wet runway conditions.
- No significant changes in ROT were observed for different headwinds/tailwinds. One might expect that ROT would be dependent on wind conditions. For example, it might be assumed that a strong headwind would result in a slower aircraft

ground speed and therefore longer ROT. However, based on this data set there is no correlation between ROT and headwind/tailwind.

- ROT data exhibits a Normal distribution.
- The average ROT for all landings (45 seconds) is well below the 50-second maximum required for operating with an in-trail separation of 2.5 NM versus 3.0 NM (for certain weight categories). It should however also be noted that with a standard deviation of 7 seconds, approximately 17% of landings will have ROT greater than 50 seconds.
- Data is required to determine the impact of low visibility on ROT. Anecdotal information indicates that low visibility operations have the greatest impact on ROT. However, this has not been documented through a data collection system such as that described in this paper.

## Acknowledgments

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## References

1. Smith, A., Cassell, R., Lee, D., Abdul-Baki, B., NASA Low Visibility Landing and Surface Operations (LVLASO) Runway Occupancy Time (ROT) Analysis, Rannoch Corp. Nov, 1998.
2. Evers C., Cassell R., *Analysis of ADS-B, ASDE-3 and Multilateration Surveillance Performance—NASA Atlanta Demonstration*, 1998 Digital Avionics Systems Conference, October 1998.
3. Weiss, W. and Thrasher, T., *Terminal Area Productivity Program Runway Occupancy Time Analysis*, CSSI, Inc., December 1996.