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Statistical Models of Runway Incursions Based on Runway Intersections and Taxiways

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Abstract

According to the Federal Aviation Administration (FAA), the number of runway incursions are rising. The configuration of runways and taxiways at airports has been identified by the FAA as possibly being related to the number of incursions. In this paper, the relationship between airport geometry factors and the number of runway incursions at specific United States airports is explored using statistical analyses. Airport operations data from the FAA Air Traffic Activity System, runway incursion data from the FAA Aviation Safety Information Analysis and Sharing System from 2009 through 2013, and airport geometry data created using airport geometry features from the FAA airport diagrams were collected. The 30 busiest airports with intersecting runways and the 30 busiest airports without intersecting runways were compared. As expected, the analysis of the data show that at $\alpha = 0.05$ level, runway incursions occur at a more frequent rate for airports with intersecting runways compared to airports with no intersecting runways. In the second phase of statistical analysis, the number of incursions per 100,000 operations at the 63 busiest United States airports was analyzed using four airport geometry factors as independent variables in regression analysis. The resulting regression equation was significant at the $\alpha = 0.05$ level and contained two independent variables: the number of crossing taxiways per runway and the number of runway intersections per runway. The equation and each variable in the equation are statistically significant and the equation explains 17.3% of the variation in incursions per 100,000 operations.

Keywords: runway incursion, runway geometry, airport safety

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Introduction

Runway incursions are potentially dangerous and increasing in number (FAA, 2012a). Airport runway and taxiway geometry may be related to incursions (FAA, 2012b). In this paper, the relationship between airport geometry factors and the number of runway incursions per 100,000 operations at specific United States airports is explored. First, the number of incursions per 100,000 operations at airports with runways that intersect other runways is compared to airports with runways that do not intersect. The 30 busiest airports with intersecting runways and the 30 busiest airports without intersecting runways are based on calendar year 2012 enplanements. Next, the number of incursions at the 63 busiest United States airports, based on enplanements during calendar year 2013, is analyzed using five airport geometry factors related to runway/runway intersections and runway/taxiway intersections. Airport operations data from the FAA (Federal Aviation Administration) Air Traffic Activity System; runway incursion data from the FAA Aviation Safety Information Analysis and Sharing System (FAA, 2014a) from January 1, 2009 to December 31, 2013; and data created using airport geometry features from the FAA airport diagrams were used.

A primary reason for this research is to better understand the relationship between runway geometries and runway incursions, with an aim to potentially reduce the occurrence of runway incursions. A runway incursion is defined by the FAA as "any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and takeoff of aircraft" (FAA, 2015, para. 1). Incursions range in severity from Category A to Category D, with Category A incursions being the most severe and Category D incursions being the least severe. A Category A incursion is one in which two or more aircraft nearly collide. A Category D incursion is simply an incident that meets the definition of a runway incursion but poses no immediate safety threats. Even more severe than Category A incursions are accidents (FAA, 2015). This research studied total incursions and did not separate incursions by category.

First, the impact of intersecting runways on runway incursions is studied to determine if the presence of intersecting runways is correlated to runway incursions. The objective is to answer the question: Is the presence of intersecting runways related to the rate of runway incursions at an airport? To answer this question, a null hypothesis is tested for significance at $\alpha = 0.05$. The null hypothesis states that the frequency of runway incursions at airports with intersecting runways is the same as at airports without intersecting runways; the alternate hypothesis is that the frequency of runway incursions is greater at airports with intersecting runways than at airports without runway intersections.

In addition to intersecting runways, the number and type of taxiway-to-runway intersections and the number of runway-to-runway intersections at airports may be associated with the number of incursions. The 63 busiest U.S. airports based on enplanements, regardless of whether runway intersections are present or not, are studied. Using airport diagrams, five types of airport geometry data were collected for each airport: the number of runway intersections per runway, the number of crossing-taxiway intersections per runway, the number of high-speed taxiway intersections per runway, the number of right-angle taxiway intersections per runway, and the number of runways. Using these data, the following research questions are asked: Do airport runway geometry factors contribute significantly to the prediction of the number of runway incursions per 100,000 operations at an airport? What are the most significant airport runway geometry factors that contribute to the number of runway incursions per 100,000 operations at an airport? Regression analysis was selected to answer these two questions.

Literature Review

Owing to the growing traffic volume and airport expansion, avoiding runway incursions has become a critical issue for aviation safety. A definition of runway incursion by the International Civil Aviation Organization (ICAO) is as follows: "Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and takeoff of aircraft" (ICAO, 2007, 1-1). In an Air Line Pilots Association white paper, increased traffic volume could be considered as one of the most significant drivers of runway incursions (Air Line Pilots Association, 2007). Additionally, owing to legacy configurations of runways and taxiways, the risk of runway incursion has increased along with the growing traffic volume and aircraft size, especially for airports designed and constructed before the jet age (FAA, n.d.). During the fiscal years of 2010 to 2012, the number of runway incursions in Categories A and B tripled from 6 to 18 in the United States (FAA, 2012a).

The FAA defines the severity classification of runway incursions from Category A to Category D. Category A includes incidents in which collisions can hardly be avoided. Category B involves incidents in which separation is reduced and there is significant potential for collisions, which may lead to time-critical corrective/evasive reactions required to prevent a collision. Category C contains incidents represented by sufficient time and/or distance to avoid collision. Category D refers to events that meet the definition of runway incursion such as the inappropriate appearance of a single vehicle, person, or aircraft on the secured area of a surface limited to the landing and departing aircraft but with no direct safety effects (FAA, 2014d).

The FAA classifies major causes of runway incursions into three categories: operational incidents, pilot deviations, and vehicle/pedestrian deviations (FAA, 2015). Pilot deviations appear when a pilot violates any Federal Aviation Regulation (FAR). Operational errors/deviations occur when air traffic controllers (ATCOs) mistakenly provide less than the minimum separation between aircraft, or between aircraft and vehicles. Vehicle/pedestrian deviations occur when pedestrians, vehicles, or other objects interfere with aircraft during movements that are not authorized by ATCO and/or ramp controllers.

A simulation exercise using the Los Angeles International Airport (LAX) reveals the significance of airport geometry layout in explaining runway incursions. This simulation modeled the existing LAX with an addition of another runway. Madson (2004) noted that the highest proportion of runway incursions at LAX occurs when an aircraft fails to stop before crossing the hold-short line of runway 25R after arriving from runway 25L and going through the high-speed exits. During the simulation, an additional center taxiway was found to reduce the risk of incursion to runway 25R by leading the aircraft turn onto a parallel taxiway. The result of debriefing controllers showed that an additional center taxiway could be effective in reducing the number of runway incursions at LAX.

Wilke, Majumdar, and Ochieng (2015) modeled the associations between an extensive list of 32 airport characteristics, causal factors, severity categories, and airport surface safety occurrences in the U.S., U.K., Norway, and New Zealand. Safety occurrences involved incursion, excursion, and foreign object damage accidents and incidents. The data included information from the specific country aircraft safety databases and from questionnaires developed and administered by the research team. Conflict points between runways and other runways, runways and taxiways, and taxiways and other taxiways are three of the 32 airport characteristics in the study. For U.S. airfields in the study, the rate of safety occurrences was associated with the number of conflict points, number of runway-to-runway conflict points, and subcontractors working on the airfield. One major finding of the study was that the severity of safety occurrences was related to both the airport geometry and the causal factors underlying the occurrences. The second major finding listed in the paper was that “safety and airports data from different countries cannot be aggregated due to their different underlying distributions” (p. 74).

Ford, Waldron, and Borener (2014) examined the data of potentially hazardous interactions (PHI) at airports under the premise that the PHIs are the precursors for surface collisions. Ford and colleagues divided the PHIs into 10 categories that are primarily congestion-related, and assert that the PHIs are a consequence of taxiway layouts constraining aircraft separation. In this study of 35 U.S. airports, 23 collisions were included between 2004 and 2014 and are considered a relatively infrequent event. A twelve-week sample of PHIs was collected at the 35 airports. The results show that “approximately 96% of PHIs involved an aircraft passing a stationary aircraft, with the most prevalent scenarios being traffic holding to enter or cross a runway, and traffic holding to enter a ramp area” (p. 12).

The literature presents evidence that airport configuration is a potential factor in runway incursions. This study seeks to investigate the relationship between runway incursions and airport taxiway and runway layout geometry. A taxiway is an airport route designed for aircraft moving from one point on the airport to another (Quilty, 2004). Two of the principles associated with taxiway system design is to minimize runway crossings and provide a sufficient turning radius. A taxiway that leads to or from a runway should have a right angle or acute angle between the respective centerlines. Standard degrees of intersection angles are 30, 45, 60, 90, 120, 135, and 150. Right-angle taxiways offer pilots the best visual perspective for both left and right turns when approaching the runway/taxiway intersection. The FAA also suggests that angled (not equal to 90 degrees) taxiways significantly increase the probability of runway incursions when the taxiway is used for crossing the runway (FAA, 2012b). However, aircraft may come to almost a full stop at perpendicular exit taxiways, and that may cause a longer runway occupancy time (Quilty, 2004). Ashford, Mumayiz, and Wright (2011) recommend that perpendicular taxiways are appropriate for runways that have 30 operations per hour or less during peak-time use. Acute taxiway angles should be 45 degrees or less from the centerline of a runway. An angled taxiway that is 45 degrees from the runway centerline is suggested for small aircraft. The recommended exit speed for 45 degree taxiways is 40 mph. Thirty-degree taxiways are appropriate for high-speed exits, and will allow runway exit speeds up to 60 mph. Intersecting taxiways with multiple acute angles should be avoided in taxiway layouts in order to reduce pilot confusion.

Appropriate runway and taxiway geometry should be applied in the airport design process to avoid the probability of runway incursion. Unfavorable taxiway design practices include but are not limited to taxiways that cross the high-speed exit, cross wide throated runways, intersect with multiple runways, and taxiway intersections that exceed the “three-node concept.” The “three-node concept” is a design principle where three or fewer branch taxiways (left, right, and straight ahead) are present when a pilot arrives at a taxiway intersection (FAA, 2012b). Furthermore, during the airport planning and design process, designers should avoid layouts that lead to a narrow space between two parallel runways, avoid airfield configurations, which may allow vehicles or aircraft to cross another active runway, and avoid taxiway layouts that lead taxiing aircraft onto runways when not landing or taking off (FAA, n.d.).

Weather conditions, visibility, and utilization of airport safety systems are other influential factors in runway incursions. Cozza and Young (2013) completed a case study focused on data from the NTSB Aviation Accident Database and the NASA Aviation Safety Reporting System (ASRS) database. The researchers applied the Pearson correlation method to evaluate the positive or negative relationship between runway incursions and three main factors of runway incursions (meteorological conditions, time of day, and presence of an air traffic control tower). Surprisingly, the

Cozza and Young (2013) analysis suggested that there is a higher rate of runway incursions during visual weather conditions, during daytime, and with the presence of a control tower.

Existing literature suggests how airport geometry features and other non-geometry factors may be related to runway incursions, excursions, foreign object damage, potentially hazardous interactions, and congestion. This research study uses the principle of parsimony in that the number of airport geometry factors is small when compared to the 32 airport characteristics in the article by Wilke. First, this study seeks to compare runway incursion rates for airports with intersecting runways and those with no intersecting runways. Second, the study in this paper focuses on airport runway-to-runway and runway-to-taxiway intersections to quantify the effect configurations may have on the rate of runway incursions per 100,000 operations.

Methodology

In this paper, the methodology is split into two stages. The first stage answers the question: Is the presence of intersecting runways related to the rate of runway incursions at an airport? The second stage answers the questions: Do runway-related airport geometry factors contribute significantly to a model of the number of runway incursions per 100,000 operations at an airport? What is the most appropriate regression model of runway-related airport geometry factors that correlates to the number of runway incursions per 100,000 operations at an airport?

In the first stage, the number of runway incursions per 100,000 operations is compared for the 30 busiest U.S. airports with intersecting runways and the 30 busiest U.S. airports without intersecting runways. This research analyzes runway incursion data from a sample of airports collected from the FAA Runway Safety Office's Runway Incursion database (FAA, 2014a). The sample of airports selected for this study was determined by identifying 60 of the busiest U.S. airports based on calendar year 2012 enplanements: the 30 busiest with intersecting runways and the 30 busiest without intersecting runways (ACAIS, 2013). U.S. airports are those located in the 50 states in the United States. Figure 1 shows an example of airports without intersecting runways and airports with intersecting runways.

Runway incursion data were collected for airports with intersecting runways and airports that do not have intersecting runways for the five-year calendar period from 2009 to 2013. The 2009 to 2013 operations data for each airport were taken from the Air Traffic Activity System (ATADS, 2014) in March 2014. The proportion of airport operations resulting in runway incursions was calculated for each airport, scaled to 100,000 airport operations. The number of runways for each of the 60 airports was determined by examining airport diagrams available online (AirNav, n.d.) in March 2014. The data were analyzed to determine if there was any statistically significant difference in the percentage of runway incursions at airports with or without intersecting runways. A one-sided test for two proportions was used to analyze the data. Total runway incursions for all airports represented the events, and total airport operations for all airports represented the trials. At $\alpha = 0.05$, rejecting the null hypothesis would provide evidence that the frequency of runway incursions at airports with intersecting runways is significantly greater than at airports without intersecting runways.

In the second stage, a more detailed analysis of the impact of runway geometry on the frequency of runway incursions was conducted using regression analysis. The dataset included the 30 largest airport hubs and 33 medium airport hubs, based on the rank of enplanements at all U.S. commercial service airports (FAA, 2014b); the number of operations from January 1, 2009 to December 31, 2013 for the 63 airports (ATADS, 2014); and the number of runway incursions for the 63 airports from January 1, 2009 to December 31, 2013 (FAA, 2014a). The dependent variable, the number of runway incursions per

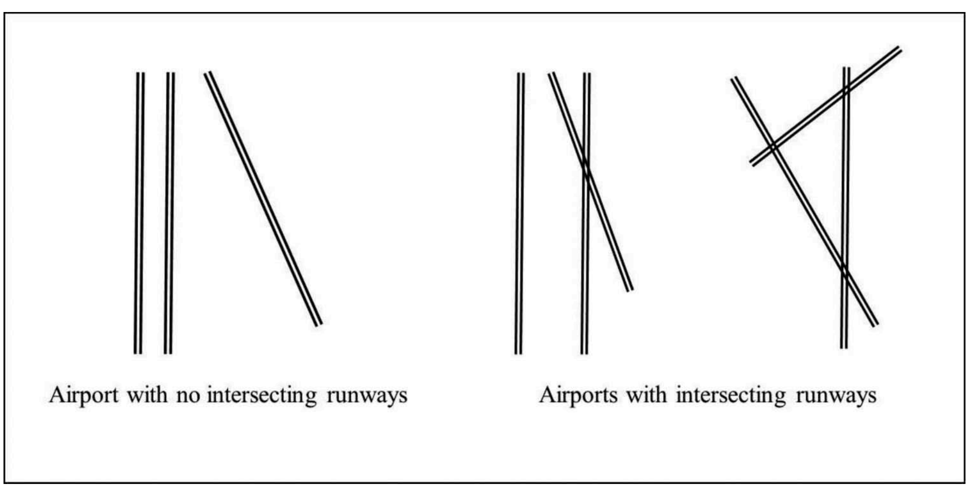

Figure 1. Example airport runway configurations with intersecting runways and without intersecting runways.

100,000 operations during this time period, was calculated by using the number of runway incursions divided by total number of operations, which was then multiplied by 100,000 as a scaling factor. Five airport geometry features were selected as quantitative independent variables for each airport: the number of intersecting runways per runway, number of crossing-taxiway intersections per runway, number of high-speed taxiway intersections per runway, number of right-angle taxiway intersections per runway, and the total number of runways at each airport. The data for these independent variables were determined by visual analysis of the features on the FAA Airport Diagrams (FAA, 2014c). See Figure 2 for examples of airports with the three different taxiway-to-runway intersections.

Data analysis was completed using commercially available, off-the-shelf, statistical software. The model was selected using the best subset model selection method. At $\alpha = 0.05$, rejecting the null hypothesis would provide evidence that the runway incursion model is significant in explaining the variations of number of runway incursions per 100,000 operations. In addition, each variable in the model is examined at $\alpha = 0.05$ to determine if the variable contributes significantly to the regression equation.

Results

The first stage of the analysis answers the question: Is the presence of intersecting runways related to the rate of runway incursions at an airport? Table 1 displays the data collected for airports with intersecting runways. Table 2 displays the data collected for airports with no intersecting runways. There was a statistically significant difference between the proportion of incursions per 100,000 operations for airports with intersecting runways of 2.02 and the proportion of 3.19 for airports without intersecting runways. The results of the analysis using a one-sided test for two binomial proportions are a z of 10.36 and a reported p-value less than 0.001. Therefore, from the data it can be shown that with $\alpha = 0.05$, airports with intersecting runways have a higher proportion of incursions per operation than airports without intersecting runways. This result is limited to the 30 busiest airports with intersecting runways as compared to the 30 busiest airports without intersecting runways. The primary assumptions for this test are that there is only one runway incursion possible for each operation reported, and that each operation is independent.

As denoted by the asterisks in Figure 3, outliers in the data include Charlotte/Douglass International Airport with one intersecting runway and a runway incursion rate of 8.03 per 100,000 operations, Dallas Love Field Airport with two intersecting runways and a runway incursion rate of 8.91 per 100,000 operations, and Tucson International Airport with no intersecting runways and a runway incursion rate of 11.02 per 100,000 operations. These outliers have a large effect on the mean of each sample; therefore, a non-parametric test for medians was selected. The Mood Median test was selected to test the hypothesis that the medians are equal because it is robust to outliers. The Chi-Square reported was 9.60 with 1 degree of freedom, resulting in a p-value of 0.002. This means that the test is significant at $\alpha = 0.05$, and we can conclude with 95% confidence that the presence of an intersecting runway affects the number of runway incursions per 100,000 operations. The 95% confidence interval for the difference in medians was between 0.38 and 1.84 incursions per

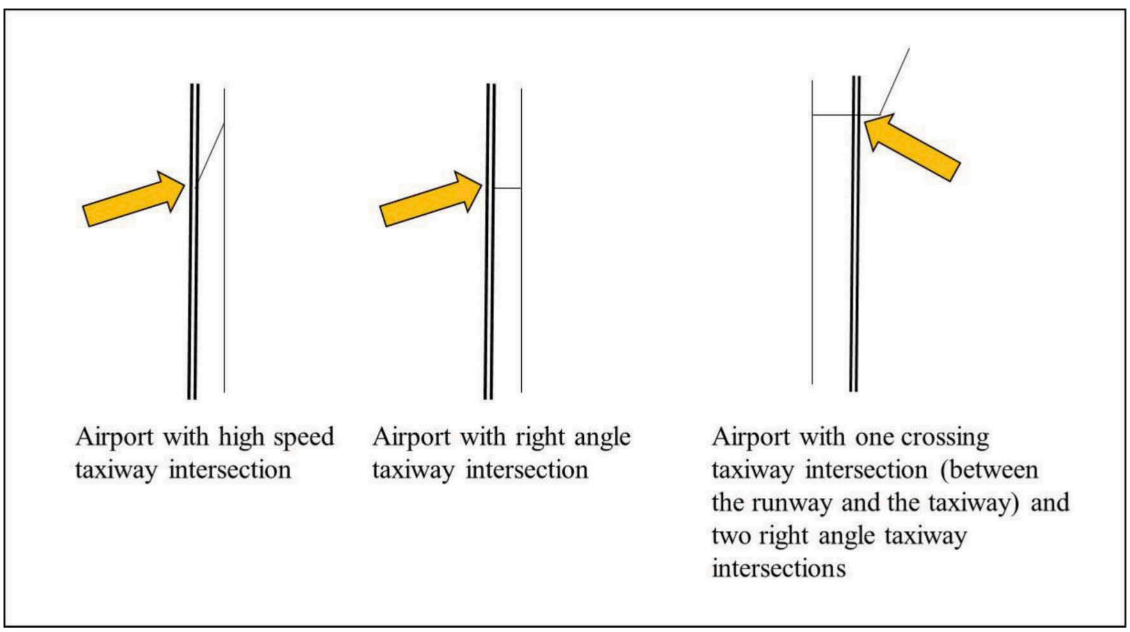

Figure 2. Example airport taxiway intersections with runways used in this study.

Table 1
Top 30 U.S. airports with intersecting runways.

CY 12 Rank[1]	FAA Identifier[2]	Runways[2]	Runway Intersection[2]	2009–2013 Airport Operations[3]	2009–2013 Runway Incursions[4]	Incursions/100,000 Operations
2	ORD	8	3	4,350,709	95	2.18
7	SFO	4	4	2,016,981	51	2.53
8	CLT	4	1	2,688,883	216	8.03
16	MSP	4	2	2,159,764	44	2.04
17	DTW	6	4	2,181,779	45	2.06
18	PHL	4	1	2,257,696	50	2.21
19	BOS	6	6	1,829,045	58	3.17
20	LGA	2	1	1,844,886	19	1.03
21	FLL	3	2	1,325,361	45	3.40
22	BWI	4	3	1,338,972	32	2.39
26	MDW	5	6	1,247,401	43	3.45
27	HNL	4	2	1,365,640	62	4.54
29	TPA	3	1	960,468	22	2.29
30	PDX	3	1	1,086,385	19	1.75
32	HOU	4	1	1,005,340	56	5.57
34	MCI	3	1	700,195	14	2.00
35	BNA	4	1	872,547	19	2.18
44	SAT	3	1	903,276	58	6.42
45	DAL	3	2	875,726	78	8.91
46	PIT	4	2	717,878	22	3.06
47	MKE	5	5	786,049	31	3.94
52	CVG	4	1	844,142	5	0.59
53	OGG	2	1	579,583	1	0.17
54	PBI	3	1	691,326	36	5.21
55	BDL	3	2	497,729	8	1.61
56	ABQ	3	1	698,855	30	4.29
57	BUF	2	1	493,034	11	2.23
61	BUR	2	1	505,790	9	1.78
62	OMA	3	2	502,325	15	2.99
63	PVD	2	1	360,979	8	2.22
				37,688,744	1,202	3.19

Note. [1]ACAIS (2013). [2]AirNav (n.d.). [3]ATADS (n.d.). [4]FAA (2014a).

100,000 operations. With this result, it makes sense to proceed to the regression modeling in the second stage where more detailed runway geometry is included.

In the second stage, a detailed analysis of the impact of runway geometry on the frequency of runway incursions was conducted using regression analysis. Table 3 shows the dataset for the 30 largest U.S. airport hubs, and Table 4 shows the dataset for the 33 U.S. medium hubs based on enplanements in calendar year 2013. In the regression analysis, there are four independent variables: crossing-taxiway intersections per runway, high-speed taxiway intersections per runway, right-angle taxiway intersections per runway, and the intersecting runways per runway. The dependent variable is incursions per 100,000 operations. It should be noted that one taxiway crossing a runway also results in two right-angle intersections between taxiways and runways; additional right-angle taxiways intersecting with runways are possible other than those that occur at taxiways crossing runways. The variable "crossing-taxiway intersections per runway" only includes the intersections of runways and taxiways; it does not include intersections of taxiways to taxiways. The reason for this selection is that the dependent variable is runway incursions per 100,000 operations, and therefore, does not include taxiway-to-taxiway incursions.

A best subsets regression was performed to find the model with the highest adjusted R-square, and if there were ties, then also the smallest standard error and the closest Mallows's Cp to the number of terms in the model. The highest adjusted R-square was 14.5% and was for the model with two independent variables: crossing-taxiway intersections per runway and runway intersections per runway. The next highest adjusted R-square was 13.1% for a model with three independent variables. Therefore, the model with two terms was selected for further regression analysis due to parsimony considerations and a higher adjusted R-square. The regression model had a p-value of 0.003, indicating that the regression model was significant. However, a visual examination of the residuals seen in Figure 4 indicated that the regression was not valid due to violating required assumption for normality of residuals. Normality of residuals is indicated on the left side of the figure. By observation, the residuals are not normal; normal residuals would hug the straight line in the top-left graph and would appear to be bell-shaped in the lower left graph.

Based on these results, a Box-Cox transformation of the dependent variable was explored. The recommended transformation function was to take the square root of the

Table 2
Top 30 U.S. airports without intersecting runways.

CY 12 Rank[1]	FAA Identifier[2]	Runways[2]	Runway Intersection[2]	2009–2013 Airport Operations[3]	2009–2013 Runway Incursions[4]	Incursions/ 100,000 Operations
1	ATL	5	0	4,685,540	85	1.81
3	LAX	4	0	2,944,967	99	3.36
4	DFW	7	0	3,266,026	56	1.71
5	DEN	6	0	3,087,147	33	1.07
6	JFK	4	0	2,061,711	31	1.50
9	LAS	4	0	2,596,595	49	1.89
10	PHX	3	0	2,252,347	36	1.60
11	IAH	5	0	2,616,032	25	0.96
12	MIA	4	0	1,912,532	58	3.03
13	MCO	4	0	1,545,506	15	0.97
14	EWR	3	0	2,082,201	36	1.73
15	SEA	3	0	1,573,554	43	2.73
24	SLC	4	0	1,735,537	53	3.05
28	SAN	1	0	949,774	9	0.95
33	OAK	4	0	889,853	8	0.90
36	AUS	2	0	859,760	15	1.74
37	RDU	3	0	947,525	11	1.16
38	SNA	2	0	976,981	47	4.81
39	SMF	2	0	566,464	2	0.35
40	CLE	3	0	944,875	27	2.86
41	MSY	2	0	609,492	13	2.13
43	SJC	3	0	673,586	27	4.01
48	RSW	1	0	410,063	4	0.98
49	IND	3	0	809,788	7	0.86
50	MEM	4	0	1,491,990	19	1.27
51	CMH	2	0	674,554	11	1.63
58	JAX	2	0	452,459	4	0.88
59	ANC	3	0	1,302,612	35	2.69
65	TUS	3	0	589,783	65	11.02
73	ELP	3	0	446,064	3	0.67
				45,955,318	926	2.02

Note. [1]ACAIS (2013). [2]AirNav (n.d.). [3]ATADS (n.d.). [4] FAA (2014a).

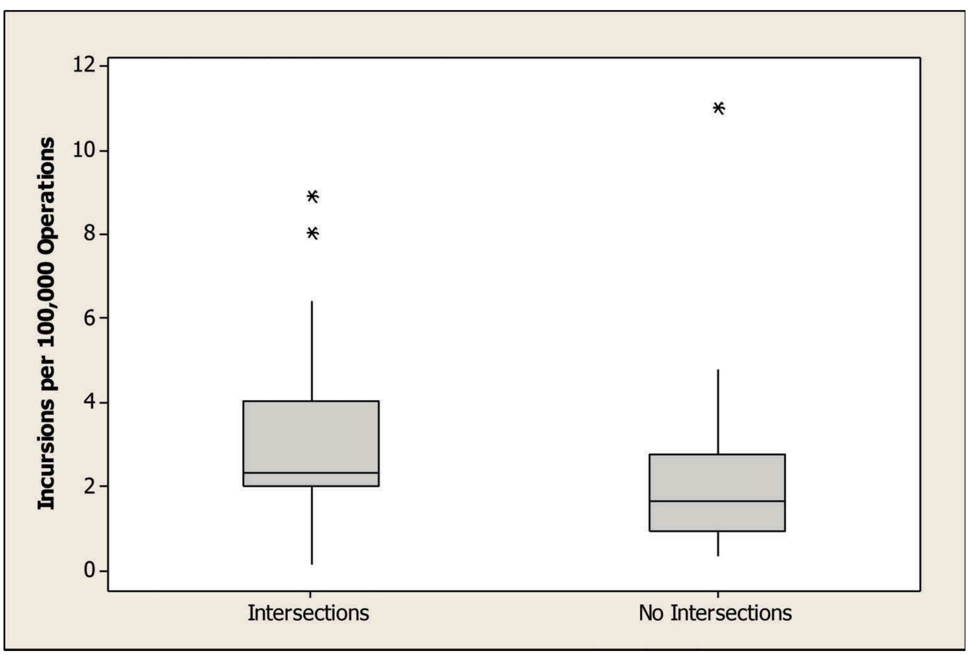

Figure 3. Incursions per 100,000 operations for the 30 busiest U.S. airports with intersecting runways and the 30 busiest U.S. airports without intersecting runways.

Table 3
Airport operations, incursions, and geometry data for the 30 largest airport hubs based on the rank of enplanements in year 2013.

Airport Code of 30 Large Airport Hubs[1]	Crossing-Taxiway Intersections Per Runway[2]	High-Speed Taxiway Intersections Per Runway[3]	Right Taxiway Intersections Per Runway[4]	Intersecting Runways Per Runway[5]	2009–2013 Runway Incursions Per 100,000 Operations[6]	Square Root of Incursions Per 100,000 Operations
ATL	5.00	4.00	10.20	0.00	1.81	1.34
LAX	4.75	5.00	9.75	0.00	3.38	1.84
ORD	4.50	3.75	7.50	0.38	2.19	1.48
DFW	7.00	5.29	15.29	0.00	1.72	1.31
DEN	0.83	3.33	7.50	0.00	1.00	1.00
JFK	4.25	2.75	10.75	0.50	1.50	1.22
SFO	9.25	2.00	13.75	1.00	2.55	1.60
CLT	5.75	4.25	10.00	0.25	2.20	1.48
LAS	5.00	2.50	9.25	0.50	1.88	1.37
PHX	8.00	9.33	16.67	0.00	1.64	1.28
MIA	4.75	9.50	9.75	0.25	3.03	1.74
IAH	3.00	5.00	6.60	0.00	0.96	0.98
EWR	5.33	3.67	12.00	0.67	1.73	1.31
MCO	3.75	3.25	7.25	0.00	0.97	0.99
SEA	5.33	3.67	8.67	0.00	2.73	1.65
MSP	8.00	2.25	14.75	0.75	2.04	1.43
DTW	4.50	2.50	5.83	0.67	2.06	1.44
BOS	2.67	1.67	5.67	0.83	3.17	1.78
PHL	5.00	2.75	10.75	0.25	2.21	1.49
LGA	4.00	7.00	8.50	0.50	1.03	1.01
FLL	7.00	18.00	21.00	0.00	3.40	1.84
BWI	4.00	1.75	5.75	0.75	2.37	1.54
IAD	1.00	5.00	5.25	0.00	1.52	1.23
MDW	4.60	1.80	6.80	1.20	3.45	1.86
DCA	4.67	1.67	5.33	1.00	2.61	1.62
SLC	3.50	4.50	6.00	0.00	3.02	1.74
HNL	5.50	1.50	7.75	0.50	4.52	2.13
SAN	6.00	3.00	12.00	0.00	0.95	0.97
TPA	5.00	2.67	13.33	0.33	2.29	1.51
PDX	3.67	3.33	8.00	0.33	1.74	1.32

Note. The data was rounded to the nearest two decimal places. [1]FAA (2014b). [2]FAA (2014c). [3]FAA (2014c). [4]FAA (2014c). [5]FAA (2014c). [6]FAA (2014a).

dependent variable (λ of 0.5). The square root of the dependent variable (incursions per 100,000 operations) is shown in the last column of Tables 3 and 4.

The best subsets regression was performed using the transformed dependent variable. The highest adjusted R-square was 17.3% and was for the model with two independent variables: number of crossing-taxiway intersections per runway and number of intersecting runways per runway. These are the same variables selected in the earlier model. The next highest adjusted R-square was 15.9% for a model with three independent variables. Therefore, the model with two terms was selected for further regression analysis. The regression model had a *p*-value of 0.001, indicating that the regression model was significant. A visual examination of the residuals seen in Figure 5 indicated that the regression was valid due to not violating required assumptions for normality of residuals and constant variance.

By observation, the residuals appear normal; the residuals hug the straight line in the top-left graph and would appear to be bell-shaped in the lower left graph. An Anderson-Darling normality test for the residuals resulted in a *p*-value of 0.143, which means the null hypothesis of normality is not rejected at $\alpha = 0.05$. On the right side of the figure, constant variance would appear as a consistent spread of the residuals for all fitted values; the spread of residuals does appear consistent.

The p-values for the two variables in the model are each less than 0.05; the standard error of the model is 0.414885. The resulting best subsets regression model is:

Square root of incursions per 100,000 operations = 1.0957 + 0.05987 (crossing-taxiway intersections per runway) + 0.4135 (intersecting runways per runway) + error.

Discussion and Conclusion

Is the presence of intersecting runways related to the rate of runway incursions at an airport? The null hypothesis tested at $\alpha = 0.05$ states that the frequency of runway incursions at airports with intersecting runways is the same as airports without intersecting runways versus the alternate hypothesis that the frequency of runway incursions is greater at airports with intersecting runways than at airports without intersecting

Table 4
Airport operations, incursions, and geometry data for the 33 medium airport hubs based on the rank of enplanements in year 2013.

Airport Code of 33 Medium Airport Hubs[1]	Crossing- Taxiway Intersections Per Runway[2]	High-Speed Taxiway Intersections Per Runway[3]	Right Taxiway Intersections Per Runway[4]	Intersecting Runways Per Runway[5]	2009-2013 Runway Incursions Per 100,000 Operations[6]	Square Root of Incursions Per 100,000 Operations
STL	2.75	2.50	6.50	0.25	1.86	1.36
HOU	4.50	2.00	10.75	1.00	5.66	2.38
BNA	2.25	2.25	7.00	0.25	2.18	1.48
AUS	0.00	1.50	5.50	0.00	1.71	1.31
MCI	1.33	4.33	6.33	0.33	2.00	1.41
OAK	1.00	1.50	4.50	0.00	0.74	0.86
MSY	2.00	0.50	7.50	0.00	2.13	1.46
SNA	4.00	1.00	8.00	0.00	3.47	1.86
RDU	0.67	0.67	6.33	0.00	1.16	1.08
CLE	2.33	3.00	5.00	0.00	2.86	1.69
SJC	6.50	0.00	17.00	0.00	3.81	1.95
SMF	0.00	1.50	4.00	0.00	0.34	0.58
SJU	2.50	3.00	8.00	0.00	3.63	1.91
DAL	4.67	3.00	5.67	0.67	8.91	2.98
SAT	5.33	1.67	11.33	0.33	6.42	2.53
PIT	4.25	4.00	6.25	0.50	3.06	1.75
RSW	6.00	10.00	8.00	0.00	0.97	0.99
IND	5.67	2.67	11.00	0.00	0.86	0.93
MKE	3.80	0.60	5.60	1.20	3.93	1.98
CMH	3.50	2.00	9.50	0.00	1.63	1.28
OGG	3.00	3.00	4.00	0.50	0.16	0.40
PBI	6.00	5.00	12.00	0.50	5.18	2.28
CVG	3.50	2.50	10.75	0.25	0.59	0.77
BDL	2.33	1.00	6.67	0.33	1.57	1.25
BUF	3.00	4.50	8.00	0.50	1.71	1.31
JAX	0.50	3.50	3.50	0.00	0.85	0.92
ABQ	5.00	4.67	10.00	0.33	3.98	1.99
ANC	5.00	2.67	5.00	0.33	2.61	1.62
MEM	5.00	3.50	12.00	0.00	1.27	1.13
OMA	5.67	2.33	9.67	0.67	2.81	1.68

Note. The data was rounded to the nearest two decimal places. [1]FAA (2014b). [2]FAA (2014c). [3]FAA (2014c). [4]FAA (2014c). [5]FAA (2014c). [6]FAA (2014a).

runways. Based on the data and $\alpha = 0.05$, it can be concluded with 95% confidence that the number of runway incursions per 100,000 operations is greater at airports with intersecting runways than at airports without intersecting runways. It was assumed that only one runway incursion can occur per airport operation for the test for two proportions. Due to the presence of outliers in the data, a Moods Median test was performed and also concluded that there is a significant difference in the medians at $\alpha = 0.05$. The limitations are that this sample only included the 30 busiest airports with at least one intersecting runway and the 30 busiest without intersecting runways. Data were not collected for Washington Dulles International Airport, Ronald Reagan Washington National Airport, and Lambert-St Louis International Airport, since runway incursion data for these airports were unavailable in the ASIAS database at the time of this study. Luis Muñoz Marín International Airport in San Juan, Puerto Rico and Ontario International Airport in Ontario, Canada were not included in this study since these airports are not in the 50 United States.

Do runway-related airport geometry factors contribute significantly to the prediction of the number of runway incursions per 100,000 operations at an airport? What are the most significant runway-related airport geometry factors that contribute to the number of runway incursions per 100,000 operations at an airport? Regression analysis was selected to answer these two questions and resulted in the model:

Square root of incursions per 100,000 operations = 1.0957 + 0.05987 (crossing-taxiway intersections per runway) + 0.4135 (intersecting runways per runway) + error.

The regression equation and each variable in the model were significant at $\alpha = 0.05$. The adjusted R-square was 17.3%, and the standard error of the model was 0.414885. Therefore, runway-related airport geometry factors do significantly contribute to the modeling of runway incursions per 100,000 operations. The most significant airport geometry factors studied were number of intersecting runways per runway and number of crossing-taxiway intersections per runway.

To use this model, the following data is required for an airport: number of crossing-taxiway intersections, number of intersecting runways, and number of runways. For example, consider a fictional airport with four runways, two intersecting runways, and three crossing-taxiway intersections. Using these values, the equation is found by substituting the values in this equation:

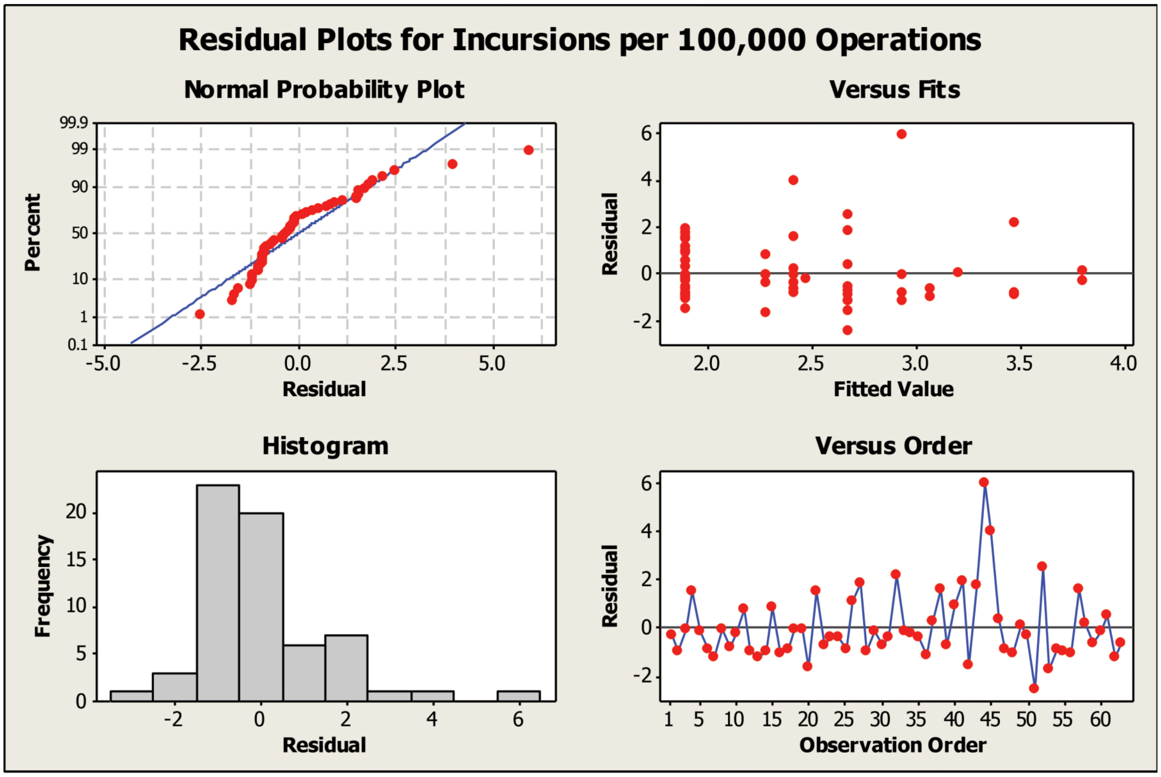

Figure 4. Residual plots for best subset model for incursions per 100,000 operations.

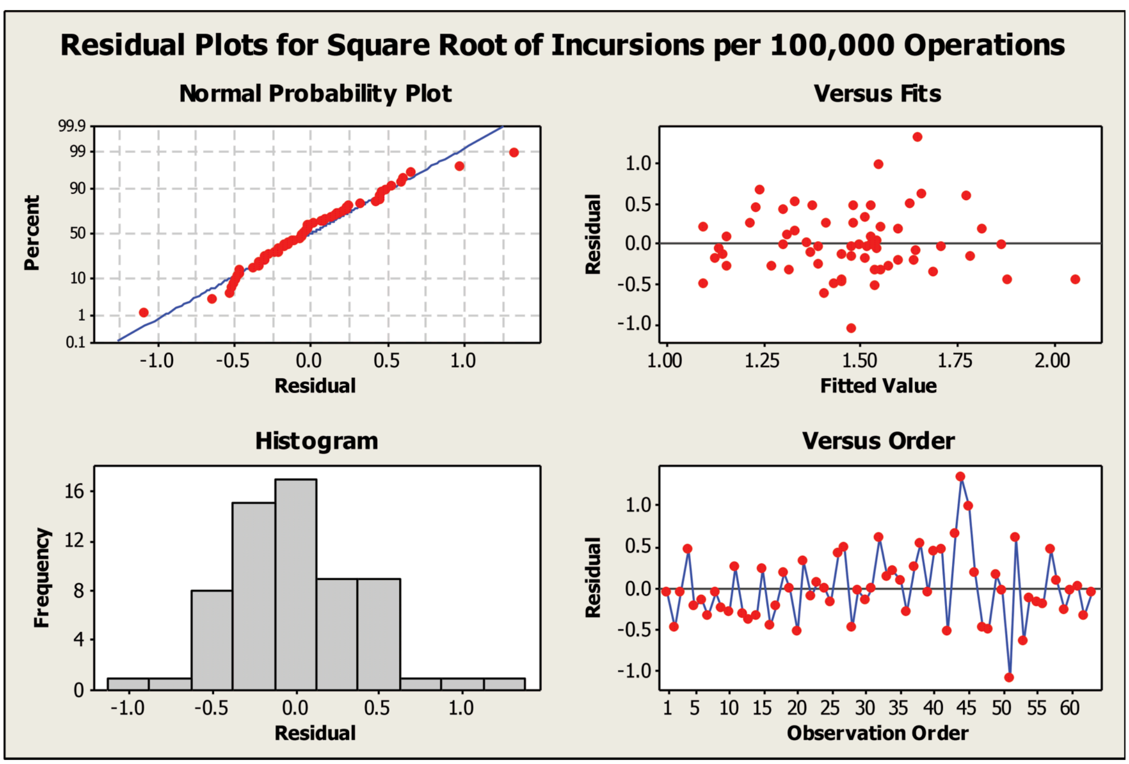

Figure 5. Residual plots for best subset model for square root of incursions per 100,000 operations.

Square root of incursions per 100,000 operations = 1.0957 + 0.05987 (crossing-taxiway intersections per runway) + 0.4135 (intersecting runways per runway)

Each step of the equation is presented:

Square root of incursions per 100,000 operations = 1.0957 + 0.05987 (3/4) + 0.4135 (2/4)

Square root of incursions per 100,000 operations = 1.0957 + 0.044903 + 0.20675

Square root of incursions per 100,000 operations = 1.347353

Then, each side of the equation is squared to result in 1.815 incursions per 100,000 operations.

However, owing to the low adjusted R-square of 17.3%, it is anticipated that any estimate made using this model may not meet the expectations of precision in practical use. Using the statistical software, a 95% confidence interval for this equation is (1.1154, 1.5793). Remembering that these values are for the square root, the 95% confidence interval for the mean is between 1.244 and 2.494 incursions per 100,000 operations. This range will not be the same for all possible values of the variables. As the values of the variables in the equation result in a value farther from the grand mean of the dependent variable, the wider the confidence interval will become.

In conclusion, the frequency of runway incursions when there are intersecting runways is significantly greater than if there were no intersecting runways for the 60 busiest airports in the 50 United States from 2009 to2013. Among runway-related airport geometry features, the number of crossing-taxiway intersections per runway and the number of intersecting runways per runway are the two significant factors in explaining runway incursions at the 63 busiest U.S. airports during calendar year 2013. Based on the models, the number of runway incursions per 100,000 operations increases as the number of crossing-taxiway intersections and intersecting runways increase.

Recommendations

This study only included the busiest airports, based on enplanements. In future research, a larger sample of U.S. airports could be included, as well as the inclusion of airports in other countries. There may be additional airport geometry factors that should be included, such as distance between intersections, width of taxiways, or airport hotspots.

The FAA Runway Safety Office Runway Incursion database (FAA, 2014a) described runway incursions using different incident type codes, such as PD, VPD, and OE/OI. Further research may be done to explore the relationship between airport configurations and specific types of runway incursions. Additionally, the data format of incident locations at airports is not sufficiently concise for researchers to build up a comprehensive dataset. Mining the incident location information from the database might be beneficial for researchers seeking a more accurate understanding of the effects those different taxiway layouts have on runway incursions.

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