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Safety Study Report on Separation Requirements for Simultaneous and Sequential Area Navigation (RNAV) Departures at Atlanta/Hartsfield International Airport (KATL)

**Flight Systems Laboratory
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August 2011

**Flight Systems Laboratory
6500 S. MacArthur Blvd.
Systems Training Building Annex, RM 217
Oklahoma City, Oklahoma 73169
Phone: (405) 954-8191**

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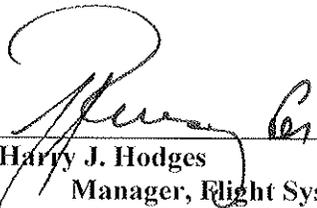
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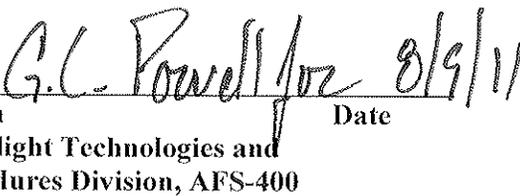
Safety Study Report on Separation Requirements for Simultaneous and Sequential
Area Navigation (RNAV) Departures at Atlanta/Hartsfield International Airport
(KATL)

Reviewed by:



Harry J. Hodges 8/9/11 Date
Manager, Flight Systems Laboratory, AFS-450

Released by:



Leslie Smith 8/9/11 Date
Manager, Flight Technologies and
Procedures Division, AFS-400

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Technical Report

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Departures at Atlanta/Hartsfield International Airport (KATL)

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12. Abstract Hartsfield-Jackson Atlanta International Airport (KATL) is seeking approval of a waiver to allow independent departure operations from various runway configurations to new departure routes that do not meet the course divergence criteria defined in the FAA's Air Traffic Control Order JO 7110.65, paragraph 5-8-3, Successive or Simultaneous Departures. Specifically, the proposed operations do not achieve the required course divergence within the allowed distance from the runway ends. The basis for the waiver is the assumed track following performance of modern Area Navigation (RNAV) capable aircraft. Only aircraft authorized to conduct terminal RNAV operations in accordance with AC90-100A would be assigned the procedures in question. The five proposed operations include two successive departure procedures where the aircraft are sequenced onto different routes that do not meet the divergence criteria and three simultaneous departures where either the divergence or distance to divergence requirements of the order are not met. The RNAV and Required Navigation Performance (RNP) Group, AJR-37, requested analytical support from the Flight Systems Laboratory (FSL), AFS-450, to determine the acceptability of these operations from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO). The results from the FSL studies would be included in the Safety Risk Management Document (SRMD) being prepared as part of the waiver request. The safety study considered results from previous RNAV departure evaluations and analyzed track dispersions from over 12,000 departures that were considered likely RNAV aircraft. The results of the analysis and the historical data support the concept of reducing departure divergence requirements for suitably equipped RNAV aircraft. Operational issues such as runway reassignments and longitudinal separation for wake protection will also require consideration.		
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Executive Summary

Hartsfield-Jackson Atlanta International Airport (KATL) is seeking approval of a waiver to allow independent departure operations from various runway configurations to Area Navigation (RNAV) departure routes that do not meet the course divergence criteria defined in the FAA's Air Traffic Control Order JO 7110.65, paragraph 5-8-3, Successive or Simultaneous Departures. Specifically, the proposed operations do not achieve the required course divergence within the allowed distance from the runway ends. The basis for the waiver is the assumed track following performance of modern Area Navigation (RNAV) capable aircraft. Only aircraft authorized to conduct terminal RNAV operations in accordance with AC90-100A would be allowed to participate in the procedures in question. The five proposed operations include two successive departure procedures where the aircraft are sequenced onto different routes that do not meet the divergence criteria and three simultaneous departures where either the divergence or distance to divergence requirements of the order are not met.

The Area Navigation (RNAV) and Required Navigation Performance (RNP) Group, AJR-37, requested analytical support from the Flight Systems Laboratory (FSL), AFS-450, to determine the acceptability of these operations from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO). The results from the FSL studies would be included in the Safety Risk Management Document (SRMD) being prepared as part of the waiver request.

The safety study considered results from previous RNAV departure evaluations and analyzed track dispersions from over 12,000 departures that were considered likely to be RNAV aircraft. Probability distribution functions were fitted to the departure tracks and used to estimate the likelihood of being off the intended track far enough to collide with the other departing aircraft (which could also be off course). Successive departures were examined to collect data on how much time passed between departures and how much speed difference might occur. Data from both the National Offload Program and the ASDE-X system installed at KATL were used in the evaluation. The study did not consider successive departures from the closely spaced pairs at KATL as those operations are not allowed by their operational practices.

The results of the analysis showed that the collision risks associated with the proposed departure pairings met the acceptance criteria selected for the study. Operational issues such as runway reassignments and longitudinal separation for wake protection will also require consideration but are not directly addressed in the report.

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1.0 Introduction

This report presents the results of an analysis of the tracking capabilities of a subset of aircraft departing from Hartsfield-Jackson Atlanta International Airport (KATL). The subset is intended to represent modern Area Navigation (RNAV) capable aircraft and was selected based on the aircraft's radar track meeting certain conditions. The tracking data was collected from the National Offload Program (NOP) data and parsed using software developed by the Flight Systems Laboratory (FSL). The distributions generated by the analysis were then used to evaluate the risks associated with particular departure operations being requested by KATL that do not meet the current design standards defined in the FAA's Air Traffic Control Order JO 7110.65, paragraph 5-8-3, Successive or Simultaneous Departures. The Area Navigation (RNAV) and Required Navigation Performance (RNP) Group, AJR-37, requested analytical support from the Flight Systems Laboratory (FSL), AFS-450, to determine the acceptability of these operations from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO). The results from the FSL study could be included in the Safety Risk Management Document (SRMD) being prepared as part of the waiver request. This section of the report describes the purpose and structure of this document, and provides a description of the problem.

1.1 Purpose and Structure of the Report

This study assessed the risks associated with proposed simultaneous and sequential independent departure operations from selected runways at Hartsfield-Jackson Atlanta International Airport. The proposed operations do not meet the current requirements defined in Air Traffic orders but intend to achieve equivalent or better safety by restricting the operations to aircraft with modern RNAV guidance. The risk assessment is based on tracking performance demonstrated during previous RNAV departure operations at other major airports and on observed departure tracking performance of RNAV aircraft at KATL.

This report defines the problem (Section 1.2), explains the study methodology (Section 2.0), and describes the data collection and parsing (Section 2.1) and the analysis (Section 2.2). Section 3 applies the track analysis to the particular operations of interest, i.e. the new departure operations. Conclusions and recommendations are given in Section 4.

Appendix A: Reich Model details the derivation of the model used in this study.
Appendix B: Johnson Distributions discusses the Johnson distributions used in the study.
Appendix C: Related Topics briefly discusses the MITRE Equivalent Lateral Spacing Operations report and the comparative risks associated with blunders. Appendix D: Sample RNAV Departure provides an example of an RNAV departure from Atlanta.

1.2 Statement of the Problem

FAA Air Traffic Control Order JO 7110.65T [1], paragraph 5-8-3, Successive or Simultaneous Departures is the current Air Traffic Control (ATC) provision governing required course separation during departures. Under those requirements, successive departures from the same runway (or parallel runways separated by less than 2500 feet) must diverge by more than 15 degrees within 1 nautical mile of the runway. Simultaneous departure courses from parallel runways separated by more than 2500 feet must diverge by more than 15 degrees immediately after departure, which is generally interpreted to mean within 1.5 nautical miles of the departure end of the runway.

Criteria for course divergence requirements during successive or simultaneous departures have historically been based on dead-reckoning (DR), i.e. no navigational guidance during the departure except perhaps magnetic heading. The high pilot workload during this phase of flight where throttles are being adjusted, landing gear raised, flaps retracted, and aircraft configuration set for climbing to the necessary altitude to join the terminal or en route structure also has an effect on aircraft tracking performance. Under these circumstances, a reduction in tracking performance is to be expected. For successive departures, there is also the obvious problem of a faster trailing aircraft catching up to a slower leading one if there was insufficient separation between the assigned courses. Finally, surveillance of the initial segment of the departure is normally limited until the aircraft climbs into radar coverage and the surveillance system establishes a track and displays it to the departure controller such that a plane that deviates from course shortly after liftoff (for whatever reason) could go undetected for a short period.

Modern RNAV aircraft, however, provide extremely accurate navigational guidance either from satellite navigation (SatNav) or inertial based systems while on the runway prior to departure or very shortly after take-off for other navigation systems. Typical Flight Management Systems (FMS) begin providing lateral navigation (LNAV) guidance at 400 to 500 feet above runway elevation. Many modern aircraft using satellite navigation have guidance while on the runway. The pilot workload issue is still present as is the potential of catching up to a slower aircraft or experiencing a course deviation shortly after liftoff, but for modern transport category aircraft, cockpit automation has reduced the workload and differences in departure speeds within the class should be significantly less than for a generic sample of all departing aircraft.

At the major airports within the United States National Airspace System (NAS), a large percentage of the aircraft using the airport are air transport types that are likely to possess modern RNAV equipment. Previous studies [2,3] have demonstrated that the tracking performance of these aircraft is much more precise than for the generic fleet. KATL is seeking to take advantage of these capabilities by designing RNAV departure routes that improve traffic flow, minimize environmental and noise impacts, and increase efficiency but do not achieve the course divergence currently required by the 7110.65 order.

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There are five new departure scenarios defined in the request:

- 1.) Successive departures from Runway 26L: Aircraft will depart on a 272 degree heading and turn within 1.2 NM of the departure end of the runway (DER) to either waypoint SNUFY at 280 degrees or MPASS at 290 degrees. At MPASS (approximately 7 NM from the DER), those aircraft will turn toward ZELAN and achieve 15 degree divergence.
- 2.) Simultaneous departures from Runways 26L and 27R: 26L traffic will proceed to SNUFY (280 degrees) and then BDODD at 282 degrees. 27R traffic will proceed to SLAWW (270 degrees) and then WESEK (270 degrees). Initial lateral separation between the runways is 4400 feet. Three nautical mile separation is achieved prior to WESEK at 14 NM from the DER.
- 3.) Successive departures from Runway 8R: Aircraft will depart on a 080 degree heading and turn within 1.0 NM of the DER to either waypoint HRSHL at 067 degrees or RONII at 080 degrees. At HRSHL (approximately 7 NM from the DER), those aircraft will turn toward KLEGG and achieve 15 degree divergence.
- 4.) Simultaneous departures from Runways 08R and 09L: 08R traffic will proceed to RONII (080 degrees at approximately 13 NM) and then BEDRK at 002 degrees. 09L traffic will proceed to LIDAS (090 degrees) and then ERWIN (090 degrees). Initial lateral separation between the runways is 4,400 feet. Course divergence is not achieved until the 08R traffic turns to BEDRK at RONII approximately 13 NM from the DER.
- 5.) Simultaneous departures from Runways 09L and 10: 09L traffic will proceed to LIDAS (090 degrees) and then ERWIN (090 degrees). The 10 traffic will turn toward GRITZ (096 degrees) within 1.0 NM of the DER. Initial lateral separation between the runways is 5,250 feet. At GRITZ (8.7 NM from DER), the traffic will turn to either HYZMN or BEDRK and achieve required course divergence.

Figure 1 shows current and proposed KATL departure routes. The routes under discussion here are indicated by the green arrows from circled numbers that correspond to the paragraphs above. An example of an RNAV departure plate with associated text is included as Appendix D.

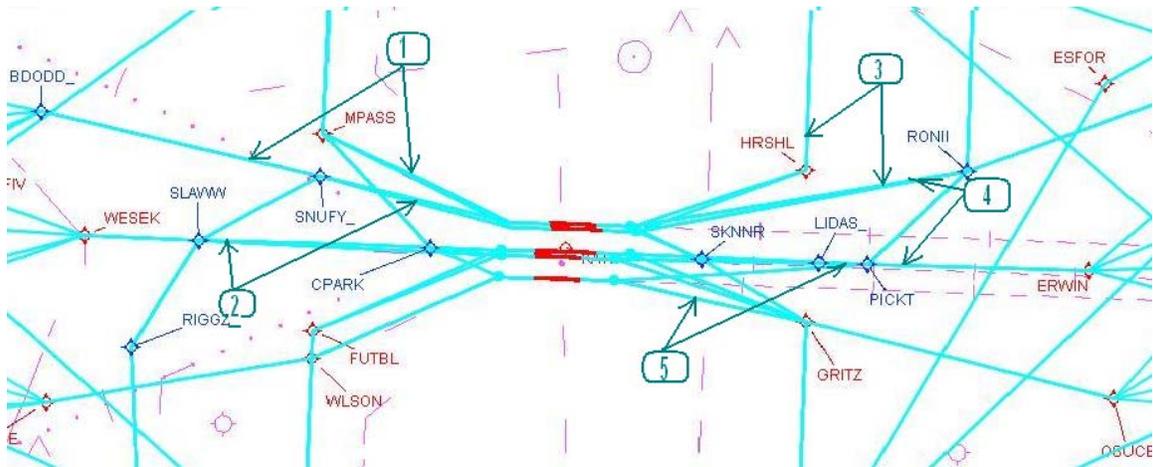


Figure 1. KATL Departure Routes

The Flight Simulation Laboratory was requested by the RNAV/RNP Group to conduct a study to evaluate the risks associated with the reduced course separation considering the improved navigation capabilities. The study may serve as supporting material to a Safety Risk Management Document (SRMD) to support a waiver request in accordance with the Air Traffic SMS manual allowing implementation of the new routes.

1.3 RNAV/RNP Considerations

The Pilot Controller Glossary [4] defines RNAV as “a method of navigation which permits aircraft operation on any desired flight path within the coverage of ground or space based navigation aids or within the limits of the capability of self-contained aids, or a combination of these.” Note that RNAV includes performance based navigation (PBN) operations as well as other operations that do not fall within the definition of PBN.

RNAV procedures are developed in accordance with AC 90-100A, “U.S. Terminal and En Route Area Navigation (RNAV) Operations” [5]. In developing AC 90-100¹, industry partners and the FAA defined the minimum criteria for RNAV systems to operate on the RNAV routes and procedures.

An RNP navigation system differs from an RNAV system primarily in that it has additional algorithms for detecting and alerting when the navigation system information might be providing incorrect information. This process is referred to as “integrity monitoring.” There must also be processes in place for monitoring Flight Technical Error, either automatically or manually, and making the pilot aware of excessive values.

¹ The AC, along with additional RNAV supporting information, is available at the Web site of the FAA Flight Technologies and Procedures Division, Flight Operations Branch (AFS-410).

1.4 Operational Considerations

This study addresses the risk associated with aircraft following the intended departure route. The study does not consider blunders, i.e. aircraft that are significantly deviating from the intended departure route. Additional consideration should be given to operational issues that may cause deviations from the intended course. One issue that surfaced in earlier RNAV departure evaluations resulted from the fairly routine practice of ATC reassigning departure runways as traffic flow affects runway queues. If the pilot failed to enter the correct departure runway following the reassignment, the aircraft would attempt to “correct” course back to the original runway’s departure track when the FMS’s LNAV was engaged following takeoff. Recently, adjustments have been made to the controller’s departure clearance procedure that may reduce this problem.

A second issue that might induce unintended course deviations is the selection of FMS leg types used in the procedure design. Certain FMS’s are not capable of flying all leg types and substitute the closest available type when necessary. Some of these substitutions can lead to early turns that effectively qualify as blunders. Most of these problems are recognized and can be addressed operationally. The issue just needs to be considered during the procedure development or SMS process.

2.0 Study Methodology

This study examined track dispersion data from earlier RNAV departure studies at KATL and other airports and also evaluated radar tracks of aircraft presumed to be RNAV equipped departing from KATL within a 10 month period (May 2009 through February 2010). The presumption was based on aircraft type and airline and the flight track’s association with known RNAV routes, i.e. if the track closely followed a path over several waypoints, including one or more turns, it was assumed to be an RNAV aircraft. Once the track was identified as RNAV, it was combined with other similar tracks, and dispersion statistics were developed at intervals along the first ten miles of the departure track past the DER. These dispersion statistics were then evaluated over the proposed departure routes to determine an appropriate risk value.

2.1 Summary of Data Used

The National Offload Program (NOP) provides access to certain air traffic data elements for qualified users. These data elements include surveillance data from many sites in the NAS including KATL. Track data for aircraft operating within 40 NM of KATL were downloaded for three periods: May 10, 2009 to June 17, 2009, December 6, 2009 to December 20, 2009, and December 27, 2009 to February 10, 2010. The data included the aircraft call sign, type, airline, report time, latitude, longitude, and altitude (as reported by the aircraft transponder).

Software tools were developed to allow visualization, selection and exclusion of tracks from the downloaded files. Two routes were selected: 26L to SNUFY to BDODD which included two small angle turns and 09L to LIDAS and ERWIN which was a straight out departure. The software tool identified departures from each runway and allowed the selection of only tracks that passed over BDODD or ERWIN (within a reasonable distance – there were no tracks parallel to the selected routes that were more than half a mile or so off the waypoint.) After BDODD and ERWIN, the tracks split off toward other waypoints or apparently at random. Tracks that did not proceed to another waypoint were excluded from consideration even though they may have been valid RNAV departures that were just cleared direct to their destination. The tool also filtered out aircraft of unknown type.

The selected tracks should serve as a conservative set of representative RNAV departures. The 09L group in particular is likely to include a significant amount of “contaminants” as there could be many non-RNAV aircraft flying due east from the airport that may have been included in the selection. Note that it is taken for granted that an RNAV aircraft will have superior tracking capability over a non-RNAV one so that incidental inclusions of non-RNAV elements will tend to make the results more conservative, hence safer.

For evaluation of successive departure operations, it was also necessary to collect data on the longitudinal separation between departures and determine what speed differentials were acceptable to the Atlanta air traffic controllers. A two week period of Airport Surface Detection Equipment-Model X (ASDE-X) data from KATL was collected and processed to identify how much time passed between one departure and the next, how much speed difference there was between a leading and trailing aircraft in a successive departure pair, and what types of aircraft were involved.

2.2 Description of the Analysis

2.2.1 Track Data Collection and Analysis

Once the test set of tracks was identified, another software tool was used to identify “pierce-points” through vertical planes spaced at 1/8 NM intervals from the departure end of the runway out to 10.0 NM. The pierce-points provided data for determining the lateral and vertical distributions of aircraft tracks as a function of range from DER. The tracks for each procedure from all three periods were combined (making the tacit assumption that they all came from the same distribution since they were all presumed to be performing the same operation.)

A third tool was used to calculate the statistics and determine probability distribution functions for both the lateral and vertical dispersions. The tools report included mean, standard deviation, skewness, and kurtosis for each distance. It also calculated the best Johnson distribution to fit the dispersion data. The Johnson family of empirical distributions is based on transformations of standard normal variates (Gaussian). The

three or four parameter Johnson functions allow a more precise fit to a set of real world data that can be easily mapped to a normal distribution allowing access to all the mathematical tools and models available for that function. Johnson distributions are covered in more detail in Appendix B. The tool also presented a plot of pierce-points at each range window with color mapping of aircraft type. A screen capture of the tool's output is shown in Figure 2.

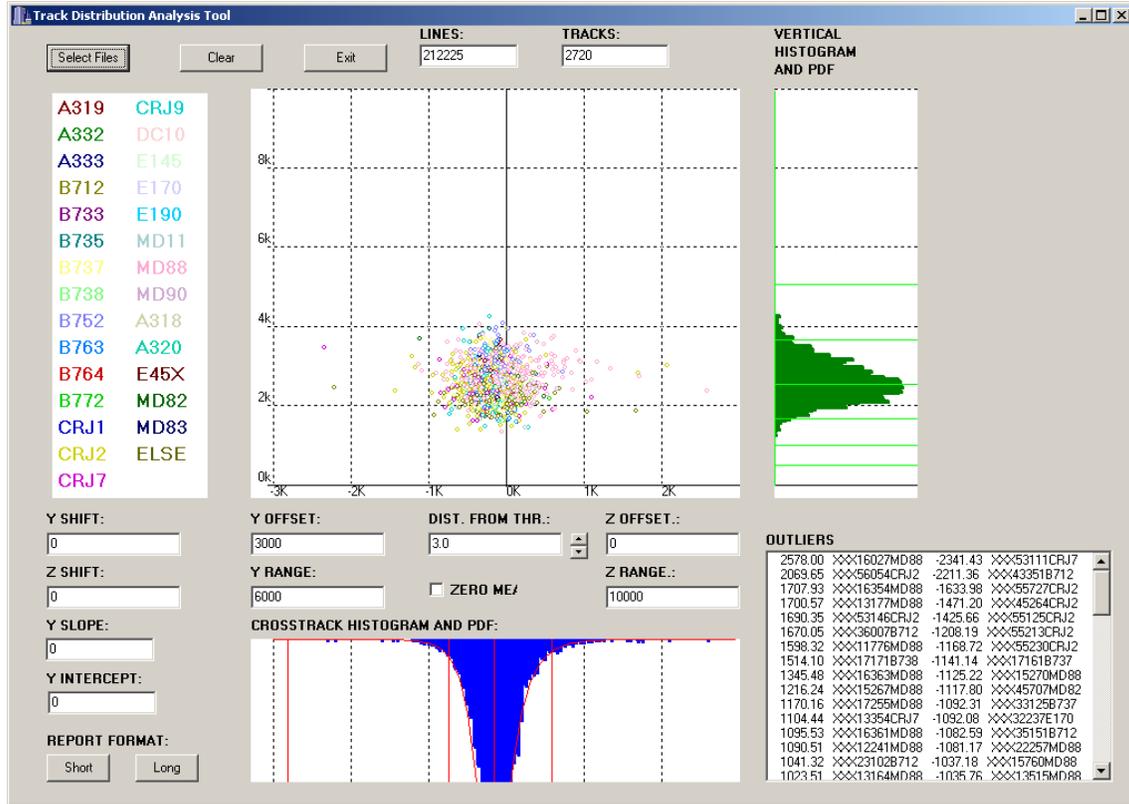


Figure 2. Track Distribution Analysis Tool

Figures 3 and 4 are plots of the standard deviations and kurtosis' of the lateral distributions of the selected tracks versus range from the DER. Standard deviation is an important measure of dispersion for reasonably well behaved data (single peaked, bell shaped curves). The kurtosis parameter is a good indicator of the thickness of the tails of a distribution. A higher value indicates the presence of a higher percentage of larger deviations than would be expected in normally distributed data.

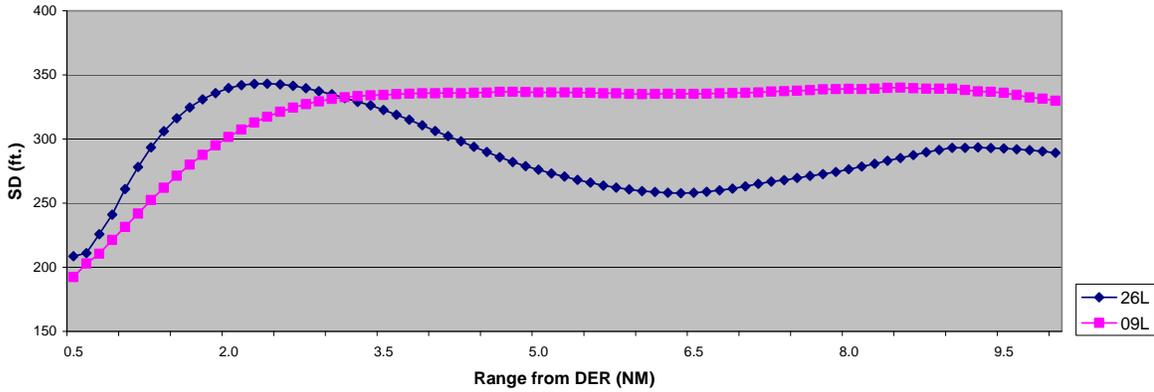


Figure 3. KATL RNAV Departures Standard Deviations

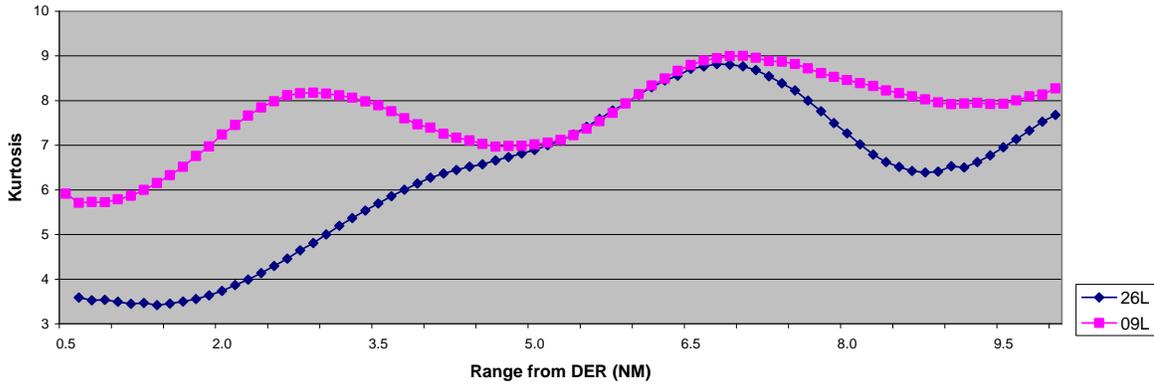


Figure 4. KATL RNAV Departures Kurtosis

Figures 5 and 6 show the mean tracks, ± 2 standard deviation (sd) curves and ± 4 sd curves for the normal and Johnson distributions and the minimum and maximum deviations for the two routes (for the lateral deviations, minimum and maximum mean greatest crosstrack deviation right and greatest crosstrack deviation left respectively). Normal (or Gaussian) sd's are indicated as GSDs in the legends. The mappings of the equivalent Johnson transforms are noted as JSDs. Figures 7 and 8 show the same data with the mean set to zero so that the dispersions can be examined separately from any track biases. Note that the normal and Johnson distributions are very close for the mean and 2 sd curves but are significantly separated by the 4 sd curves. This reflects the kurtotic nature of the data which basically means there were more tracks with larger deviations than one would expect in normally distributed data.

For completeness, Figures 9 and 10 show the same data for the vertical profiles. At some of the larger ranges, the Johnson function identification process became unstable and produced invalid values. Those sections of the plots were simply deleted since they had no relevance to the analysis.

The statistical descriptions of the track dispersions allow generation of probability distribution functions (PDFs) at the particular ranges from the DER. Given the fairly smooth curves shown in Figures 3 and 4 (and the physics of flight operations), it is reasonable to assume those PDFs are also accurate descriptions of the track distributions between the measurement points.

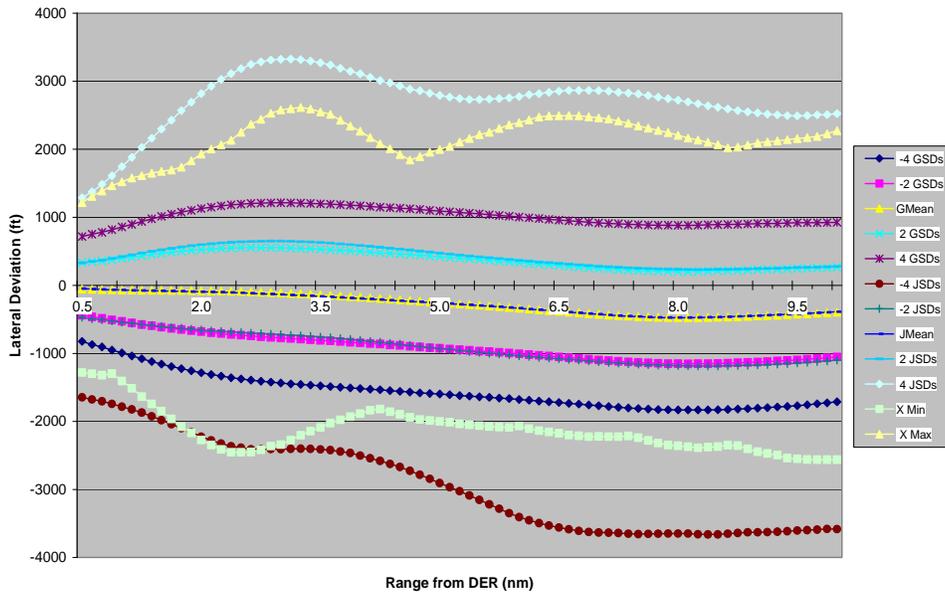


Figure 5. KATLR09L RNAV Departures Lateral Statistics

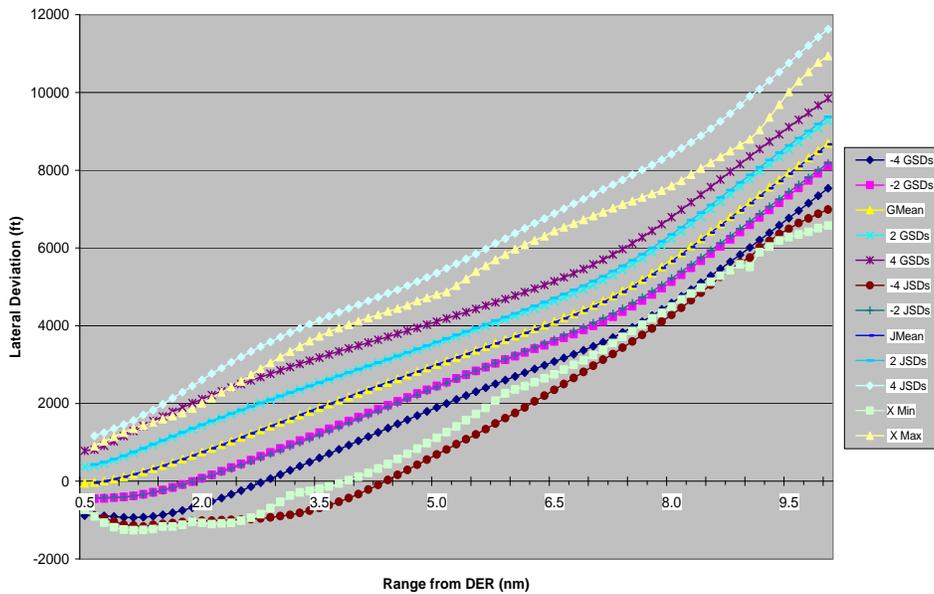


Figure 6. KATLR26L RNAV Departures Lateral Statistics

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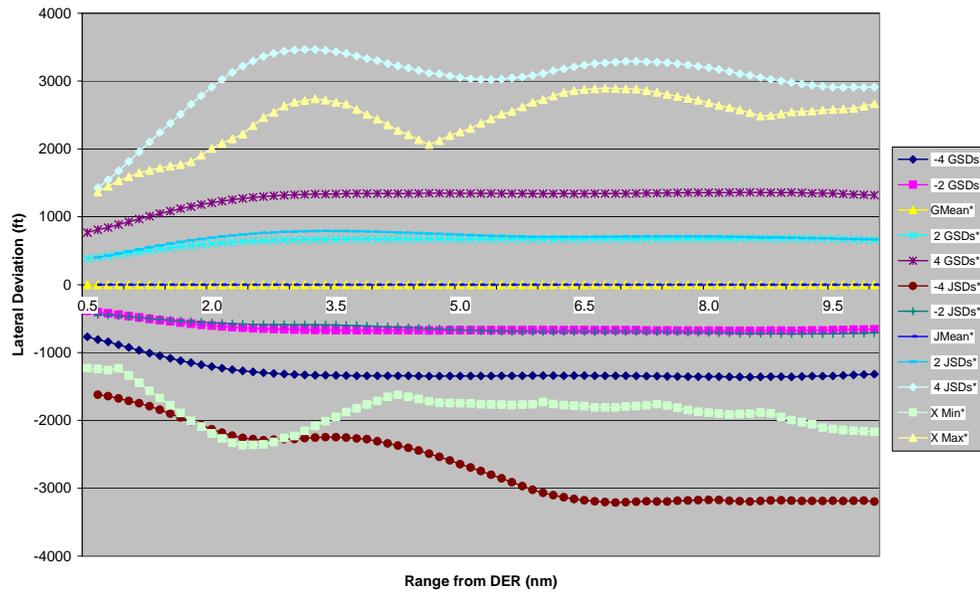


Figure 7. KATLR09L RNAV Departures Lateral Statistics (with mean set to zero)

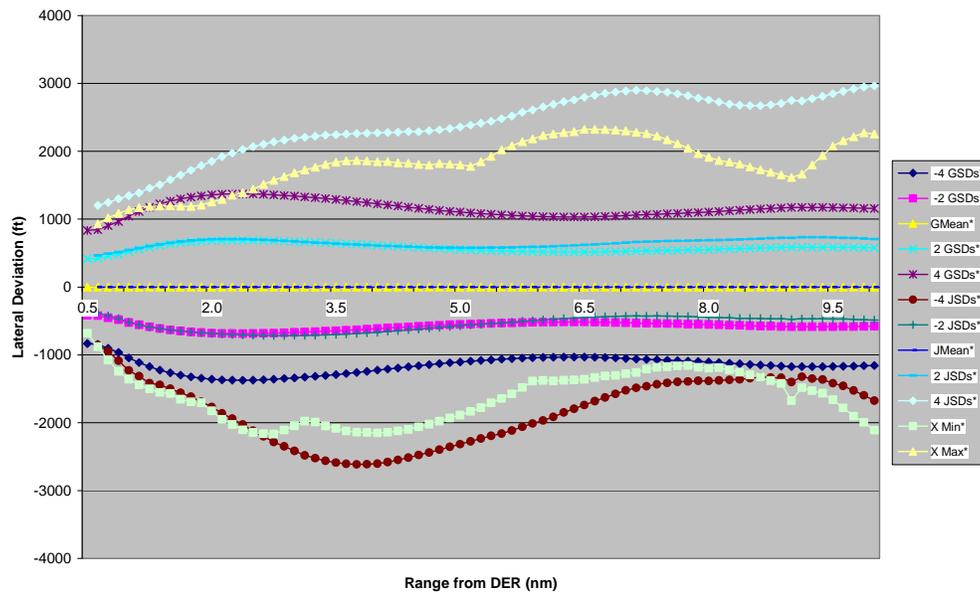


Figure 8. KATLR26L RNAV Departures Lateral Statistics (with mean set to zero)

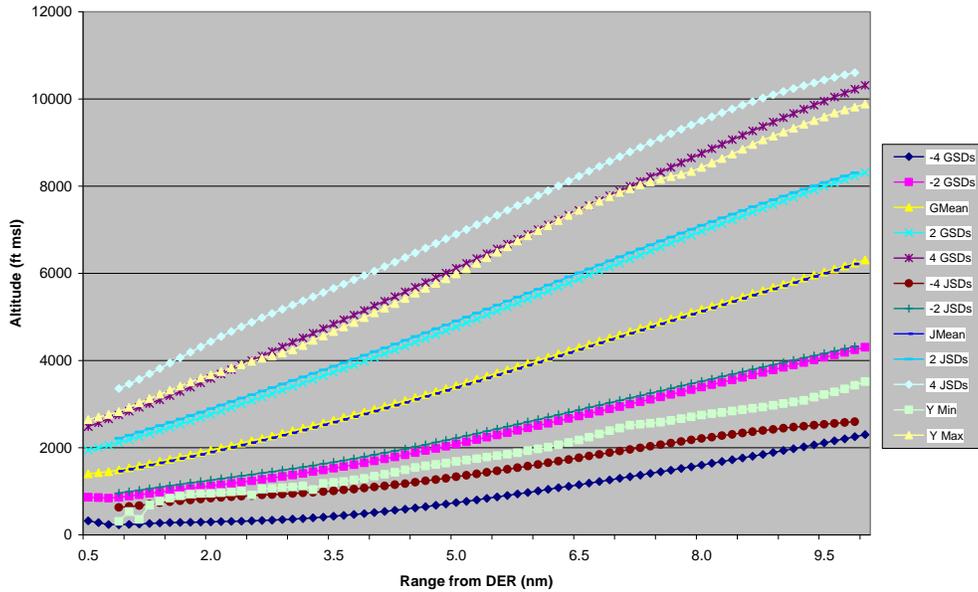


Figure 9. KATLR09L RNAV Departures Vertical Statistics

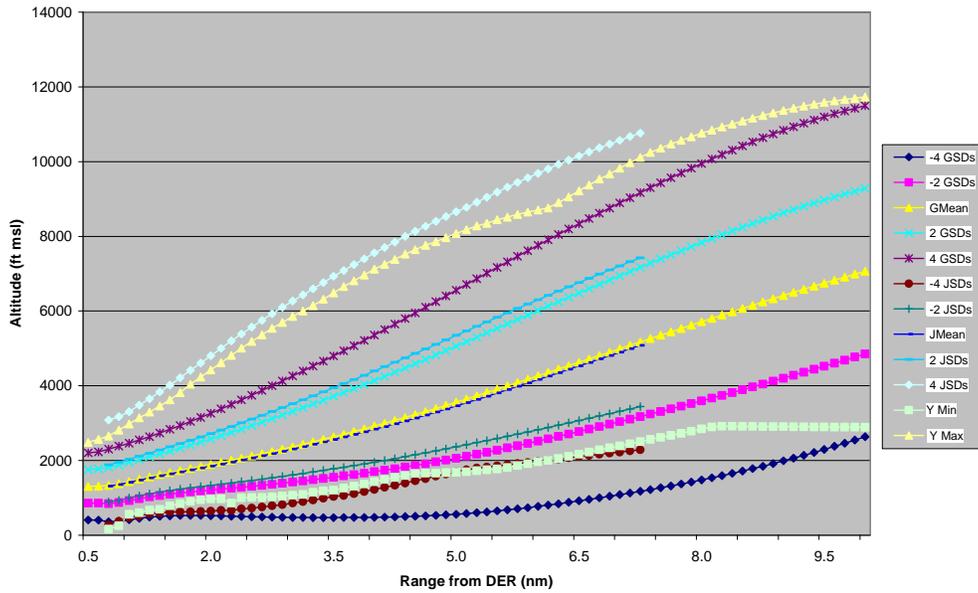


Figure 10. KATLR26L RNAV Departures Vertical Statistics

2.2.2 Simultaneous Departure Evaluation

For the simultaneous departure case, if several worst-case assumptions are made, then the PDFs derived above can be used to calculate the probability of one aircraft being off the intended course far enough to potentially collide with the other aircraft from the adjacent course (which may also be off course) for that distance from the DER. The assumptions

are that the aircraft are longitudinally and vertically aligned (side-by-side at the same altitude) and flying at approximately the same speed for the duration of the period of evaluation. The evaluation is also restricted to airspace between the two tracks. While the probability distributions fitted to the data extend from $-\infty$ to $+\infty$, the evaluation is not including scenarios where one aircraft crosses the other aircraft track and collides with it. If the collision risk for this extremely unlikely occurrence meets the acceptable level of risk, it is reasonable to assume the operation should be safe. Significant deviations from the intended course, i.e. blunders are addressed in Appendix C.2.

A modified Reich model was used for the evaluation of the simultaneous departures. The Reich model [7] is an internationally recognized standard [8] for estimation of risks associated with collisions between aircraft in flight. The derivation of the modification is shown in Appendix A. The Reich model calculates a risk value based on separation between the two intended paths factoring in the size of the respective aircraft and their relative velocities and the distribution of their flight tracks.

For mathematical convenience, one aircraft is modeled as a rectangular solid with a width equal to the sum of both wingspans, a length equal to the combined length of the two airplanes, and height equal to their combined height, and the other aircraft is modeled as a point. For normal use a generic size is picked for the rectangle based on a representative large aircraft of the fleet mix of interest.

The relative speeds are typically based partly on collected data and partly on conservative assumptions. Since this study is modeling a “worst case” scenario where the two aircraft are aligned longitudinally and vertically, two of the speed components are therefore set to zero. Appendix A uses this assumption to evaluate the probability of a TCW which is defined there in equation 6 and repeated here,

$$P(\text{TCW}) = |\dot{y}(S_y)| \int_{-\infty}^{\infty} f(u)g(u - S_y)du$$

where the first term is the relative lateral speed of the two aircraft and the integral calculates the overlap of the two track distributions, f and g being the track dispersion distributions for the two aircraft and u being the lateral distance from the centerline of runway 1 and S_y being the lateral separation between tracks.

Since the study is determining the risk for the operation (the part of the departure prior to achieving the required course or distance separation) rather than for a particular time interval, it was decided to use the lateral motion of the aircraft over a fixed distance rather than their velocity. Given the update rate of the source data, a 1 nautical mile interval was reasonable. The relative lateral motion is determined by examining the rate of change of the cross track deviations shown in the radar tracks. This data was used to develop a lateral motion probability distribution for the particular tracks. To minimize any radar error that might convolve itself into the solution, the track data was smoothed using a low pass filter. Since the tracks are diverging, the average lateral motion will not

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result in a collision. To produce a positive closing rate, it is necessary to look at values two to four standard deviations from the mean of **both** distributions. For a normal distribution, this would correspond to a probability between 2.5×10^{-3} and 1.0×10^{-9} . Analysis of the data showed that it was generally slightly leptokurtic or had thicker tails than would be expected in a normal distribution but given the presence of non-RNAV "contaminants", assuming normality is not unreasonable. If the final result is marginal, it may be necessary to examine this assumption more closely.

Assuming normality, it is possible to estimate the optimal (most conservative) lateral motion values from the data. Table 1a shows the relative divergence rates using values between 1.9 and 4 standard deviations (σ) at 0.1σ intervals, i.e. the mean lateral rate of one track plus $x \sigma$'s minus the mean rate of the other track plus $x \sigma$'s for x equal to 1.9, 2.0, ..., 4.0, for distances from 1 to 9 miles from the departure threshold. Negative numbers indicate a positive closing rate. As can be seen from the data, the probability of a positive closing rate at most distances is negligible (less than 1.0×10^{-9}) but from 1 to 5 mile ranges, some significant rates are seen. Table 1b gives the probability of an event more than x standard deviations from the mean. The table shows the product of the closing rates and their probability (which is where the assumption of normality is critical) and indicates that the maximum risk is from aircraft between 1 and 2 nautical miles from the DER that have lateral motions approximately 2.2 standard deviations from the respective means.

Table 1a. Closing Rates for Lateral Motion

σ	Divergence Rates (ft/NM)								
	1 NM	2 NM	3 NM	4 NM	5 NM	6 NM	7 NM	8 NM	9 NM
1.9	21.936	258.634	304.863	310.395	343.738	432.395	795.237	1109.370	1138.208
2.0	-11.071	231.524	279.802	285.901	321.115	411.639	774.567	1089.922	1120.588
2.1	-44.078	204.414	254.740	261.406	298.492	390.882	753.896	1070.475	1102.969
2.2	-77.085	177.304	229.678	236.912	275.869	370.126	733.226	1051.027	1085.349
2.3	-110.092	150.195	204.616	212.417	253.246	349.369	712.556	1031.580	1067.730
2.4	-143.099	123.085	179.555	187.922	230.622	328.613	691.885	1012.133	1050.110
2.5	-176.106	95.975	154.493	163.428	207.999	307.856	671.215	992.685	1032.491
2.6	-209.113	68.865	129.431	138.933	185.376	287.100	650.545	973.238	1014.872
2.7	-242.121	41.755	104.369	114.439	162.753	266.344	629.874	953.791	997.252
2.8	-275.128	14.645	79.308	89.944	140.130	245.587	609.204	934.343	979.633
2.9	-308.135	-12.464	54.246	65.449	117.506	224.831	588.533	914.896	962.013
3.0	-341.142	-39.574	29.184	40.955	94.883	204.074	567.863	895.448	944.394
3.1	-374.149	-66.684	4.122	16.460	72.260	183.318	547.193	876.001	926.774
3.2	-407.156	-93.794	-20.939	-8.034	49.637	162.561	526.522	856.554	909.155
3.3	-440.163	-120.904	-46.001	-32.529	27.014	141.805	505.852	837.106	891.535
3.4	-473.170	-148.013	-71.063	-57.024	4.390	121.049	485.182	817.659	873.916
3.5	-506.177	-175.123	-96.125	-81.518	-18.233	100.292	464.511	798.211	856.297
3.6	-539.184	-202.233	-121.186	-106.013	-40.856	79.536	443.841	778.764	838.677
3.7	-572.191	-229.343	-146.248	-130.507	-63.479	58.779	423.170	759.317	821.058
3.8	-605.198	-256.453	-171.310	-155.002	-86.102	38.023	402.500	739.869	803.438
3.9	-638.206	-283.563	-196.371	-179.497	-108.725	17.267	381.830	720.422	785.819
4.0	-671.213	-310.672	-221.433	-203.991	-131.349	-3.490	361.159	700.974	768.199

Table 1b. Product of Closing Rate and the Probability of that Rate

σ	$P(\sigma)^2$	Product of Rate and $P(\sigma)^2$				
		1 NM	2 NM	3 NM	4 NM	5 NM
1.9	8.25E-04					
2.0	5.18E-04	5.73E-03				
2.1	3.19E-04	1.41E-02				
2.2	1.93E-04	1.49E-02				
2.3	1.15E-04	1.27E-02				
2.4	6.72E-05	9.62E-03				
2.5	3.86E-05	6.79E-03				
2.6	2.17E-05	4.54E-03				
2.7	1.20E-05	2.91E-03				
2.8	6.53E-06	1.80E-03				
2.9	3.48E-06	1.07E-03	4.34E-05			
3.0	1.82E-06	6.22E-04	7.21E-05			
3.1	9.36E-07	3.50E-04	6.24E-05			
3.2	4.72E-07	1.92E-04	4.43E-05	9.89E-06	3.79E-06	
3.3	2.34E-07	1.03E-04	2.83E-05	1.08E-05	7.60E-06	
3.4	1.14E-07	5.37E-05	1.68E-05	8.07E-06	6.47E-06	
3.5	5.41E-08	2.74E-05	9.48E-06	5.20E-06	4.41E-06	9.87E-07
3.6	2.53E-08	1.36E-05	5.12E-06	3.07E-06	2.68E-06	1.03E-06
3.7	1.16E-08	6.65E-06	2.67E-06	1.70E-06	1.52E-06	7.38E-07
3.8	5.23E-09	3.17E-06	1.34E-06	8.97E-07	8.11E-07	4.51E-07
3.9	2.31E-09	1.48E-06	6.56E-07	4.54E-07	4.15E-07	2.52E-07
4.0	1.00E-09	6.73E-07	3.12E-07	2.22E-07	2.05E-07	1.32E-07

The crosstrack position of the aircraft attaining this speed also needs to be considered. It would seem reasonable to expect aircraft that were significantly off course to have a higher probability of having a velocity component toward the intended track. However, analysis of the data showed very low correlation between the lateral speed and the crosstrack deviation. Figures 11 - 16 show the distribution of lateral motion vs. crosstrack deviation at 2, 5, and 8 miles from the departure threshold ends of runways 9L (a straight out departure) and 26L (a 10 degree turn starting a mile out). The lateral motion value is the number of feet it moves perpendicular to the extended runway centerline in the next nautical mile. The distribution of values above and below a lateral motion of 0 for runway 09L or about 750 for runway 26L shows that there is about an equal likelihood of motions in either direction. Note that the crosstrack positions and lateral motion values on the runway 26L data are the distances from the runway centerline and relative to it so all three data sets have displaced means. The 8 mile data set includes data near a second course change (at SNUFY) so the relative motion is even greater.

The figures also show the best fit lines for each set of data. Descriptive statistics for the six data sets including the R value for the line fit are shown in Table 2. The R value is a

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measure of the regression fit between 0.0 and 1.0 with a value near 1.0 indicating a good fit to the line. The values in Table 2 do not suggest a good fit to a line. Examination of the plots does not support consideration of a higher order curve fit. The means for each runway correlate to the offsets mentioned above.

Based on this evaluation, it is reasonable to use the actual track separations in the Reich model analysis. If the data had shown a strong consistent negative correlation between lateral motion and crosstrack position (which was the expected outcome), then the separation between two aircraft converging at rates that were several standard deviations off the mean would have been expected to be further apart.

Table 2. Lateral Motion Statistics

	9L			26L		
	2 NM	5 NM	8 NM	2 NM	5 NM	8 NM
Mean	-32.7867	-83.6564	25.6455	758.3421	734.2508	1495.6928
Std. Dev.	119.9039	111.9769	79.6488	151.1699	114.2550	114.8251
Skewness	0.0344	-0.9590	-0.3461	0.2104	0.5518	-0.5354
Kurtosis	2.1891	6.0215	5.4793	1.5289	3.0952	12.2551
Multiple R	0.0611	0.1780	0.1143	0.2592	0.3410	0.0606
Count	5402	5405	5405	6194	6194	6194

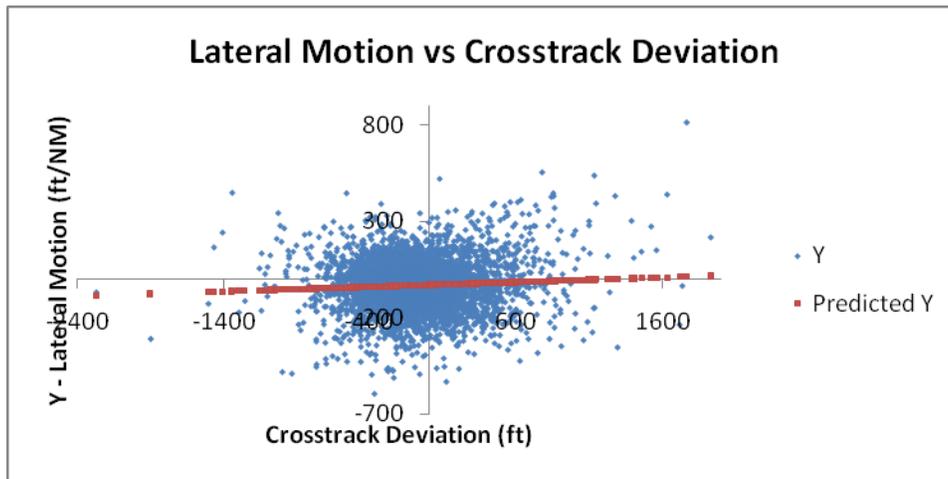


Figure 11. Runway 9L 2 NM from DER

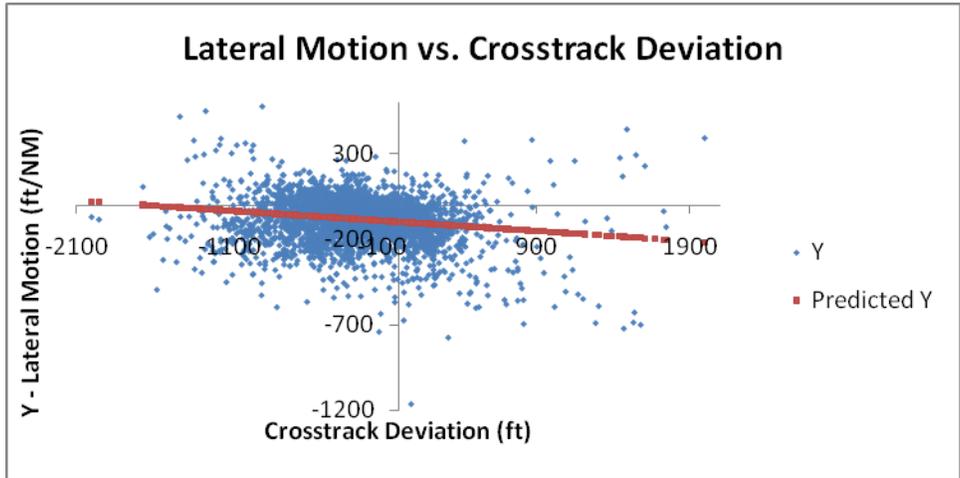


Figure 12. Runway 9L 5 NM from DER

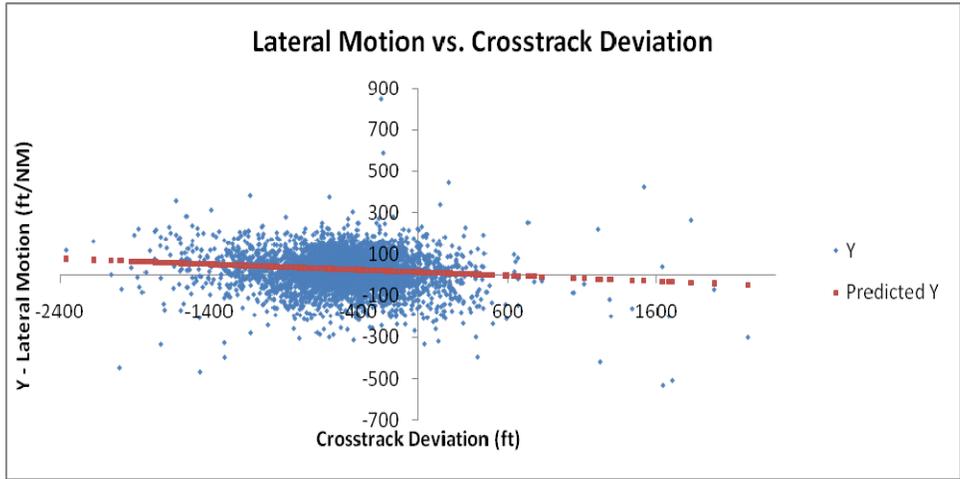


Figure 13. Runway 9L 8 NM from DER

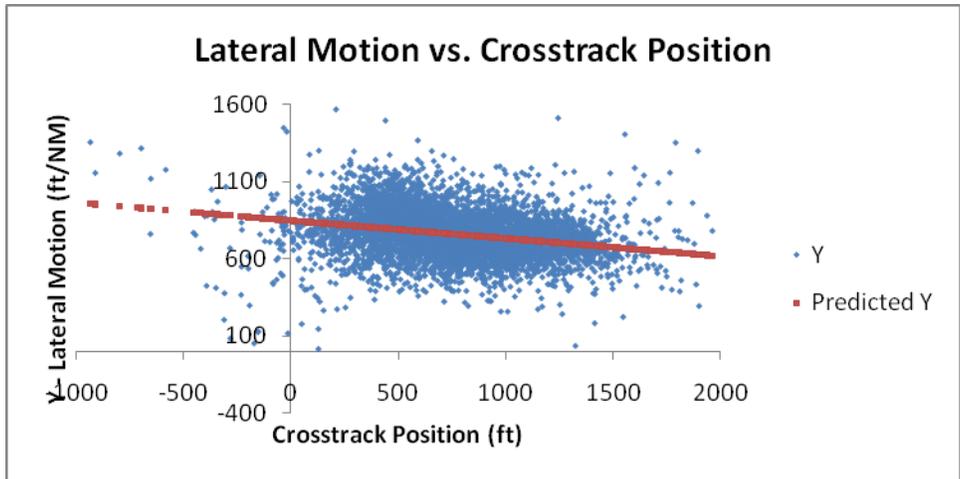


Figure 14. Runway 26L 2 NM from DER

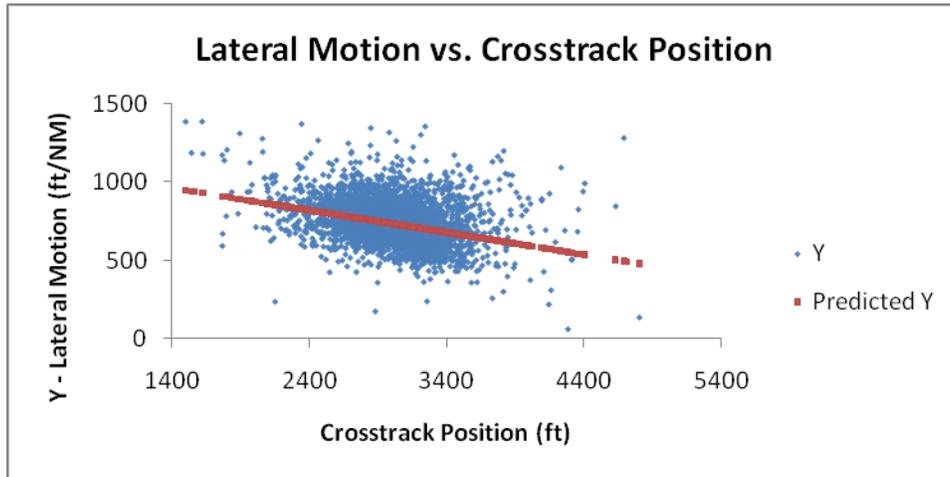


Figure 15. Runway 26L 5 NM from DER

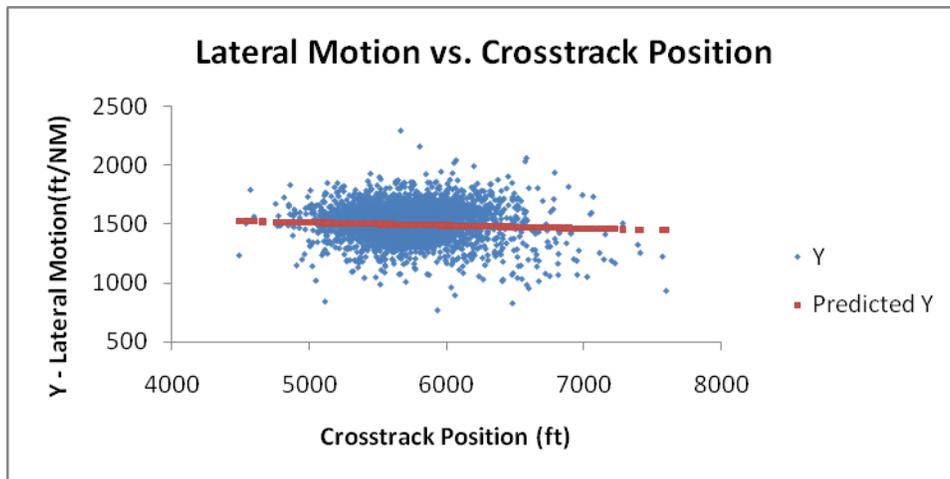


Figure 16. Runway 26L 8 NM from DER

Since the aircraft are on diverging courses, the track separation is steadily increasing. While the statistics indicate that this does not significantly impact the lateral motion values, it will affect the probability of overlap (the farther from centerline, the lower the likelihood of the aircraft being there.) If the risk is calculated at 1 nautical mile intervals from the departure threshold to the point that either course or distance separation is achieved, using the lateral motion and track separation at the start of each interval, and these values are summed, the result should be a reasonably conservative estimate for the total risk for the operation.

2.2.3 Sequential Departure Evaluation

For sequential departures from the same runway, a collision can obviously only occur if the trailing aircraft catches up to the leading one. If that occurs, then the probability that

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the aircraft are at the same altitude and are each far enough off the intended course, in opposite directions, to collide must be evaluated. As the courses are diverging, the longer it takes the trailing aircraft to catch the leader, the farther off the course(s) the aircraft need(s) to be in order to collide. On the other hand, both aircraft start off from the same runway so their initial lateral separation is zero rather than four or five thousand feet as in the simultaneous cases. Table 3 lists the distances in nautical miles required for the trailing aircraft flying at speed v_2 to catch up to the leader flying at v_1 for various combinations of delays between the departures and airspeed differentials.

Table 3. Catch Up Distances

Δt (sec)	v_1 (kts)	v_2 (kts)	Dist (nm)	Δt (sec)	v_1 (kts)	v_2 (kts)	Dist (nm)	Δt (sec)	v_1 (kts)	v_2 (kts)	Dist (nm)
45	120	125	37.5	45	140	145	50.8	45	160	165	66.0
60	120	125	50.0	60	140	145	67.7	60	160	165	88.0
75	120	125	62.5	75	140	145	84.6	75	160	165	110.0
90	120	125	75.0	90	140	145	101.5	90	160	165	132.0
105	120	125	87.5	105	140	145	118.4	105	160	165	154.0
120	120	125	100.0	120	140	145	135.3	120	160	165	176.0
45	120	135	13.5	45	140	155	18.1	45	160	175	23.3
60	120	135	18.0	60	140	155	24.1	60	160	175	31.1
75	120	135	22.5	75	140	155	30.1	75	160	175	38.9
90	120	135	27.0	90	140	155	36.2	90	160	175	46.7
105	120	135	31.5	105	140	155	42.2	105	160	175	54.4
120	120	135	36.0	120	140	155	48.2	120	160	175	62.2
45	120	145	8.7	45	140	165	11.6	45	160	185	14.8
60	120	145	11.6	60	140	165	15.4	60	160	185	19.7
75	120	145	14.5	75	140	165	19.3	75	160	185	24.7
90	120	145	17.4	90	140	165	23.1	90	160	185	29.6
105	120	145	20.3	105	140	165	27.0	105	160	185	34.5
120	120	145	23.2	120	140	165	30.8	120	160	185	39.5
45	120	155	6.6	45	140	175	8.8	45	160	195	11.1
60	120	155	8.9	60	140	175	11.7	60	160	195	14.9
75	120	155	11.1	75	140	175	14.6	75	160	195	18.6
90	120	155	13.3	90	140	175	17.5	90	160	195	22.3
105	120	155	15.5	105	140	175	20.4	105	160	195	26.0
120	120	155	17.7	120	140	175	23.3	120	160	195	29.7

Since both aircraft will be accelerating significantly during the procedure, the distances in the table should only be considered an estimate but almost all of the calculated values are well beyond distances where the Atlanta procedures will have achieved the required separation or divergence. Values highlighted in red/bold indicate cases that are close to the distance the proposed Atlanta sequential departures extend before achieving the required divergence or separation. It is also likely that aircraft with large differences in departure speeds would have significantly different climb performance creating vertical separation.

ATC operational practice is a critical factor in determining the probability of the trailing aircraft catching the leader and how long it takes for that to occur. Sequential departures

from the same runway are normally separated by either a specific time interval or visually confirmed take-off of the lead aircraft. Relevant standards are defined in [1] but operational experience is also a factor. For instance, ATC may be expecting a slower lead aircraft to be making a significant course change immediately after departure and would release a significantly faster departure as soon as the lead aircraft is off the ground. Aircraft type, take-off weight, wind speed, and other factors influence how the time between departure releases affects in-trail separation.

ASDE-X data from Atlanta collected from two departure runways over a two week period were scanned to examine normal separation distances and times, aircraft types, and speed differentials at different points along the runway. This data is not an optimal sample as the reduced divergence operations were not in place when it was collected but it should provide a baseline to determine if operational modifications will have to be made to safely run the desired departure procedures, i.e. enforcing a one minute separation between departures or something similar. The ASDE-X data, which is based on transponder responses, appeared to have a number of anomalous values, especially in the indicated airspeed (IAS) field where there were many entries that seemed either extremely high or extremely low for the given aircraft type. Clearly extreme values (such as 645 knots over the DER) were removed from the dataset but a number of questionable entries remain.

Figure 17 is a histogram of separation times at the DERs of the two runways for all departures that were less than 3 minutes apart. Figure 18 is a histogram of the IASs over the DERs for all departures that were less than 3 minutes apart. And Figure 19 shows the difference in IAS over the DER for all pairs that departed within 2 minutes of each other with negative values indicating the trailing aircraft is that much faster than the leading one. Note that aircraft passing over the DER are generally still accelerating and the larger values are frequently cases where the leading aircraft lifted off farther down the runway or is climbing at a higher rate than the trailing one, sacrificing speed for altitude.

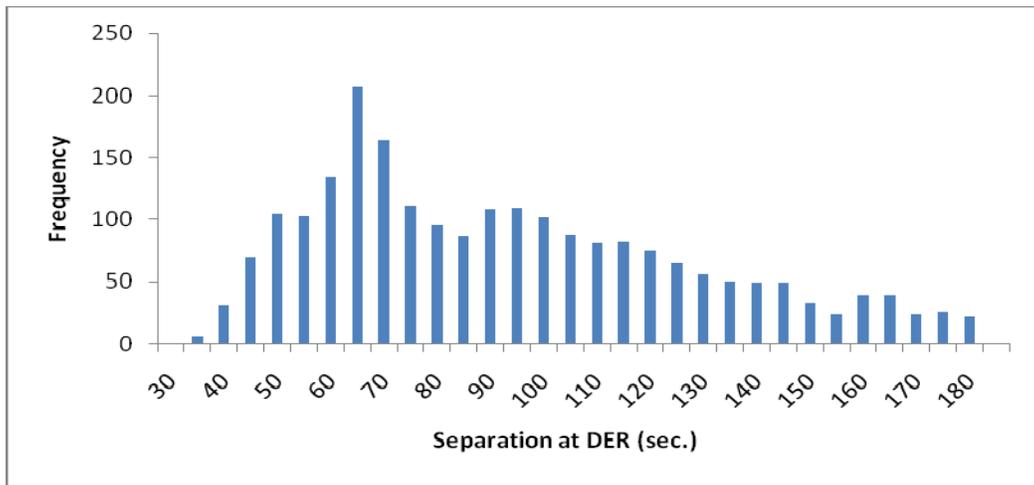


Figure 17. Time Separation between Successive Departures over the DER

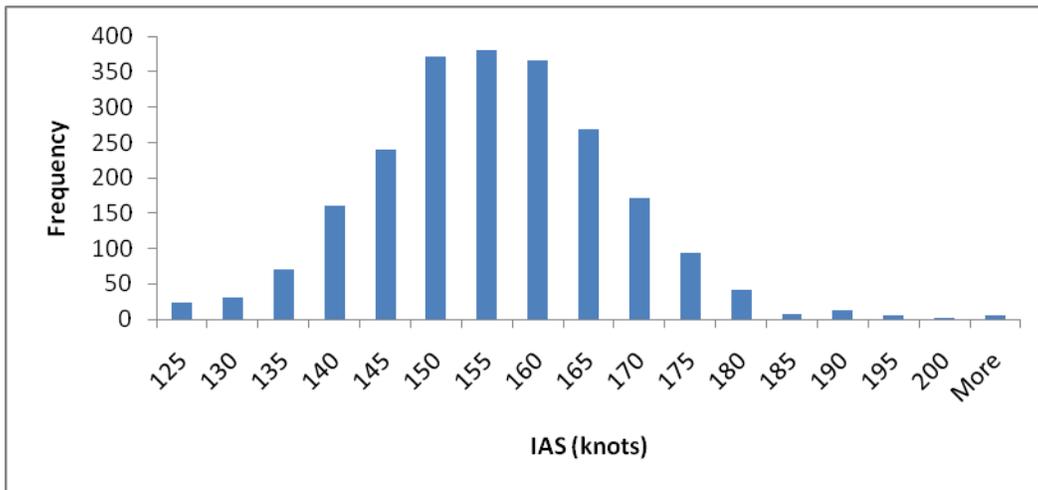


Figure 18. Indicated Airspeeds for Departures within 3 Minutes of Each Other

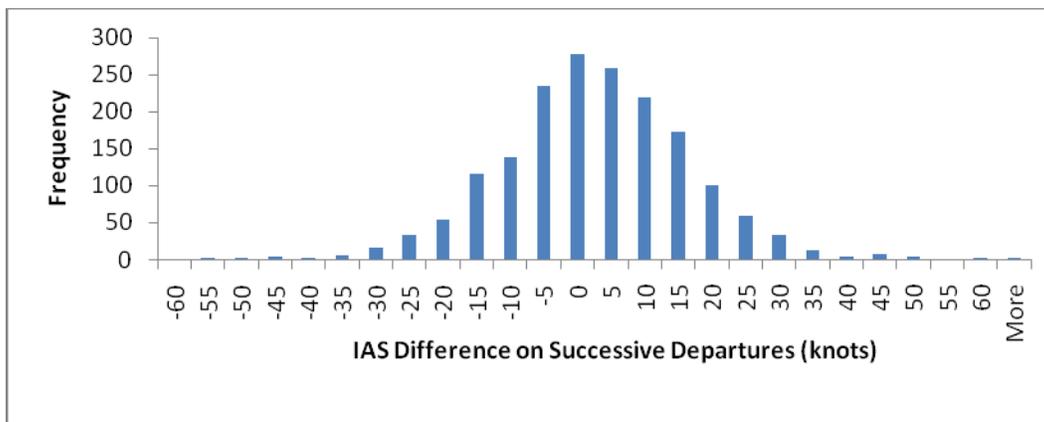


Figure 19. IAS Deltas over the DER for Departures within 2 minutes of Each Other

Enhanced Traffic Management System Counts (ETMSC) data for 2009 Atlanta operations is shown in Table 4 with only those aircraft types having 5 or more departures per day included to show the relative percentages of different aircraft types.

Table 4. Various Aircraft Departure Counts for CY2009 at KATL

Aircraft Type	2009 Departure Count
A319 - Airbus A319	2,946
B712 - Boeing 717-200	55,114
B735 - Boeing 737-500	2,343
B737 - Boeing 737-700	29,543
B738 - Boeing 737-800	18,241
B752 - Boeing 757-200	58,020
B763 - Boeing 767-300	13,202
B764 - Boeing 767-400	3,351
B772 - Boeing 777-200	1,971
C208 - Cessna 208 Caravan	3,491
CRJ2 - Bombardier CRJ-200/Challenger 800	105,566
CRJ7 - Bombardier CRJ-700	40,135
CRJ9 - Bombardier CRJ-900	26,193
E145 - Embraer ERJ-145	2,380
E170 - Embraer 170	12,262
E190 - Embraer 190	1,991
MD82 - Boeing (Douglas) MD 82	3,597
MD88 - Boeing (Douglas) MD 88	74,569
MD90 - Boeing (Douglas) MD 90	3,243
SF34 - Saab SF 340	2,239

2.3 Suitability of Selected Radar Tracks

The two sets of departure data analyzed for the study are very representative of the proposed simultaneous departure procedures. In procedure 2, runway 26L has a ten degree right turn starting a mile off the end of the runway which is exactly what the track data collected from 26L does. The runway 27R traffic proceeds essentially straight out on the runway heading just as does the tracks collected from 09L. Procedure 4 also has a 10 degree turn for traffic off of 08R and a straight out course for the runway 09L traffic. If procedure 2 is safe, procedure 4 should also be safe. Procedure 5 has a greater initial separation but a smaller turn angle than either of the other departures. The traffic off of runway 10 only turns 6 degrees south while the 09L traffic proceeds on runway heading. The runway 10 traffic can be modeled by rotating the 26L traffic 4 degrees in and the 09L traffic is doing exactly what the collected track data is.

3.0 Data Analysis and Risk Evaluation

This section defines the acceptability of the results for operational implementation and examines the results of the simulation.

The Target Level of Safety (TLS) is the maximum acceptable risk associated with an operation. For the purposes of this analysis, a TLS of 1.0×10^{-9} per operation will be considered an acceptable level of risk. Note that risk here is considered as collisions per operation rather than per flight hour. This value is our interpretation of the intent of the Air Traffic Organization Safety Management System Manual’s limit on the occurrence of catastrophic events.

3.1 Analysis for Simultaneous Departure Cases

3.1.1 Procedure 2

Simultaneous departures from Runways 26L and 27R: 26L traffic will proceed to SNUFY (280 degrees) and then BDODD at 282 degrees. 27R traffic will proceed to SLAWW (270 degrees) and then WESEK (270 degrees). Initial lateral separation between the runways is 4400 feet. Three nautical mile separation is achieved prior to WESEK at 14 NM from the DER.

The tool described in section 2.2.1 also calculated the probability of overlap by convolving the two distribution functions selected based on the descriptions in section 2.3. Table 5 shows the resulting overlap probability at each mile along with the closing rate terms calculated in section 2.2.2 and the resultant risk per mile and total risk. The risk is calculated at the 2.2 standard deviation value of the lateral motion, the 3.0 value, the 3.3 value, and a value using the worst case standard deviation at each nautical mile.

Table 5. Procedure 2 Risk Calculations

Range	P(Overlap)	2.2 SDs	Risk	3 SDs	Risk	3.3 SDs	Risk	Worst	Risk
1	9.94E-11	0.0149	1.48E-12	6.22E-04	6.18E-14	1.03E-04	1.02E-14	1.49E-02	1.48E-12
2	7.44E-11			7.21E-05	5.37E-15	2.83E-05	2.10E-15	7.21E-05	5.37E-15
3	2.46E-11					1.08E-05	2.64E-16	1.08E-05	2.64E-16
4	1.08E-11					7.60E-06	8.21E-17	1.08E-05	1.16E-16
5	1.34E-12							1.03E-06	1.39E-18
6	1.31E-13								
7	1.47E-15								
8	<1.00E-15								
9	<1.00E-15								
Total Risk			1.48E-12		6.72E-14		1.27E-14		1.49E-12

As the table shows, the worst case risk for scenario 2 is 1.49×10^{-12} , which is well below the acceptable level of risk, 1.0×10^{-9} collisions per operation.

3.1.2 Procedure 4

Simultaneous departures from Runways 08R and 09L: 08R traffic will proceed to RONII (080 degrees at approximately 13 NM) and then BEDRK at 002 degrees. 09L traffic will proceed to LIDAS (090 degrees) and then ERWIN (090 degrees). Initial lateral separation between the runways is 4,400 feet. Course divergence is not achieved until the 08R traffic turns to BEDRK at RONII approximately 13 NM from the DER.

Procedure 4 is essentially a mirror image of Procedure 2. The minor differences in tracking because of the small turn at SNUFY in Procedure 2 are too far out to make significant contributions to the total risk. The risk for Procedure 4 should also be approximately 1.49×10^{-12} , which is well below the acceptable level of risk, 1.0×10^{-9} .

3.1.3 Procedure 5

Simultaneous departures from Runways 09L and 10: 09L traffic will proceed to LIDAS (090 degrees) and then ERWIN (090 degrees). The 10 traffic will turn toward GRITZ (096 degrees) within 1.0 NM of the DER. Initial lateral separation between the runways is 5,250 feet. At GRITZ (8.7 NM from DER), the traffic will turn to either HYZMN or BEDRK and achieve required course divergence.

The overlap probabilities are calculated by rotating the track with the 10 degree turn inward 4 degrees to replicate the proposed departure and setting the initial track separation to 5250 feet. The resulting values are shown in Table 6.

Table 6. Procedure 5 Risk Calculations

Range	P(Overlap)	2.2 SDs	Risk	3 SDs	Risk	3.3 SDs	Risk	Worst	Risk
1	1.87E-11	0.0149	2.79E-13	6.22E-04	1.16E-14	1.03E-04	1.92E-15	1.49E-02	2.79E-13
2	1.79E-11			7.21E-05	1.29E-15	2.83E-05	5.06E-16	7.21E-05	1.29E-15
3	5.81E-12					1.08E-05	6.25E-17	1.08E-05	6.25E-17
4	3.07E-12					7.60E-06	2.33E-17	1.08E-05	3.30E-17
5	4.37E-13							1.03E-06	4.52E-19
6	4.71E-14								
7	<1.00E-15								
8	<1.00E-15								
9	<1.00E-15								
Total Risk			2.79E-13		1.29E-14		2.52E-15		2.80E-13

The worst case total risk for Procedure 5 is 2.80×10^{-13} , which is well below the acceptable level of risk, 1.0×10^{-9} .

3.2 Analysis for Sequential Departure Cases

3.2.1 Procedures 1 and 3

Successive departures from Runway 26L: Aircraft will depart on a 272 degree heading and turn within 1.2 NM of the departure end of the runway (DER) to either waypoint SNUFY at 280 degrees or MPASS at 290 degrees. At MPASS (approximately 7 NM from the DER), those aircraft will turn toward ZELAN and achieve 15 degree divergence.

Successive departures from Runway 8R: Aircraft will depart on a 080 degree heading and turn within 1.0 NM of the DER to either waypoint HRSHL at 067 degrees or RONII at 080 degrees. At HRSHL (approximately 7 NM from the DER), those aircraft will turn toward KLEGG and achieve 15 degree divergence.

There is not a practical way to quantify the collision risk associated with sequential departures from the same runway due to the number of variables involved in the trailing aircraft catching up with the leading one. For the catch up point to be closer to the DER than the point where required divergence or separation is achieved, there must be a relatively short period between the departures (a low probability based on the collected data) and a significant speed differential with the trailing aircraft being the faster (also a low probability). The likelihood of catching up increases with a very slow leading aircraft (another low probability). Even if all those low probability events occur, the divergent courses create a large lateral separation at any reasonable catch up distance which will reduce the probability of overlap to a very small value (approximately 1.0×10^{-10} at 5 miles from the DER). ATC also makes a crucial contribution to ensuring a safe separation between departing aircraft which would be extremely difficult to model (but is one reason the preceding probabilities are so low).

4.0 Results and Conclusions

This study addressed the risk associated with reducing the divergence requirements for five RNAV departures, three simultaneous departures and two sequential departures, at Hartsfield-Jackson Atlanta International Airport. The intent was to determine if the collision risks associated with each operation exceeded the acceptable risk level of 1.0×10^{-9} collisions per operation. The results are based on the runway geometry and traffic mix and flows at KATL and should not be applied elsewhere without additional studies.

4.1 Simultaneous Departure Procedure Results

For the simultaneous departures, a quantitative analysis was performed using a modified Reich model and radar track data collected at the airport. The model assumed that the departure times and vertical and longitudinal velocities are all equal so that the departing aircraft are continually side by side to model a “worst case”. Probability distribution

functions were fitted to the NOP track data to calculate the likelihood of lateral overlap. Lateral motion distributions were determined and the probabilities of several different closing rates was determined. The Reich model uses these values to calculate a total risk for an operation.

All three simultaneous departure procedures met the acceptable safety levels.

4.2 Sequential Departure Procedure Results

The sequential departure procedures were not as susceptible to quantitative analysis due to the many variables (including human factors) involved in a departure catching up to the previous departure from the same runway. However examination of many of the parameters associated with sequential operations strongly indicated that the probability of collision was much less than the acceptable risk level.

Both sequential departure procedures met the acceptable safety levels.

4.3 Caveats

This study did not consider risks associated with wake turbulence encounters or the possibility of blunders during the departure (blunders are briefly addressed in Appendix C.2). The study did not consider sequential departures from different runways less than 2500 feet apart. Although that is a possibility at Atlanta with the airport geometry, it was not part of the procedure descriptions provided and Atlanta Air Traffic has indicated that such operations are very rare and in any case would not be allowed to use the reduced divergence procedures.

Appendix A: Reich Model

Departure Probability Analysis

The TCV for this hazard is the collision with another aircraft that is departing at the same level and strictly along side it.

The probability of a TCV for this scenario is the sum of the probabilities of the three mutually exclusive types of collision of the two aircraft²:

1. a side-to-side collision (C_s),
2. a top-to-bottom collision (C_t),
3. or a nose-to-tail collision (C_n).

That is, $P(\text{TCV}) = P(C_s) + P(C_t) + P(C_n)$. (A1)

The probability of a top-to-bottom collision is taken to be zero, since the departing aircraft are assumed to be at the same level. Also, the probability of a nose-to-tail collision is taken to be zero, since the aircraft are assumed to be longitudinally adjacent.

Therefore, only a side-to-side collision is relevant.

The Probability of a Side-To-Side Collision, $P(C_s)$

Let the target (first) aircraft's intended track be the $y = 0$ axis and (assuming the tracks are S NM apart), the adjacent (second) aircraft's intended track will be the line $y = S_y$. (See Figure A1) so that the tracks are separated by S_y NM.

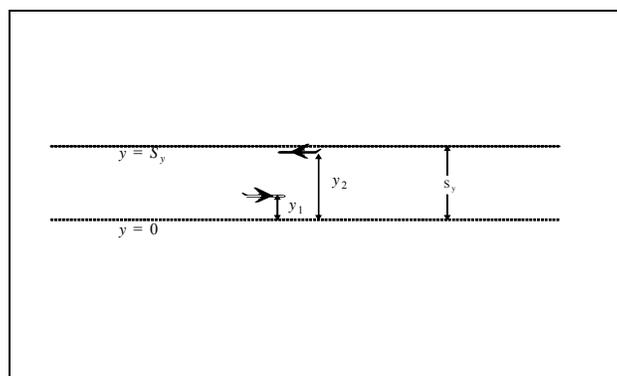


Figure A1 Mathematical Model

² This probability analysis follows that of Moek [6] for lateral separation, which in turn is based on the Reich Model [7] and is also the methodology recommended in the ICAO "Manual on Airspace Planning Methodology for Determining Separation Minima" [8].

Assume that the wingspan and length of each aircraft is λ NM. A side-to-side collision occurs only when the aircraft move into lateral overlap during that period of adjacency, and also happen to be in vertical overlap when they move into lateral overlap. Since the aircraft motion in the three dimensions is assumed to be independent, the probability of a side-to-side collision, $P(C_s)$, can be taken to be the product of:

- the duration of the period of (longitudinal) adjacency: 1 hour
- the rate of entry into lateral overlap: $N_y(S_y)$ occurrences per hour
- the probability of vertical overlap: $P_z(0) = 1$.

$$\text{That is, } P(C_s) = N_y(S_y)P_z(0) = N_y(S_y)(1). \quad (\text{A2})$$

Since, from Equation 1, the probability of a TCV for this scenario is $P(\text{TCV}_2) = P(C_s) + P(C_t) + P(C_n)$, then

$$P(\text{TCV}) = N_y(S_y) + 0 + 0.$$

Let $|\dot{y}(S_y)|$ denote the lateral passing speed of the two aircraft, that is their relative lateral approach speed. Therefore, $\frac{2\lambda_y}{|\dot{y}(S_y)|}$ is the average duration of a lateral overlap in hours.

Since $N_y(S_y)$ is the hourly rate of entry into lateral overlap and $P_y(S_y)$ is the probability that the two aircraft are in lateral overlap, then

$$P_y(S_y) \approx N_y(S_y) \frac{2\lambda_y}{|\dot{y}(S_y)|}. \text{ Therefore, } N_y(S_y) \approx P_y(S_y) \frac{|\dot{y}(S_y)|}{2\lambda_y}. \text{ So equation 2 can be written:}$$

$$P(\text{TCV}) = P_y(S_y) \frac{|\dot{y}(S_y)|}{2\lambda_y}. \quad (\text{A3})$$

The lateral passing speed, $|\dot{y}(S_y)|$, that is, the speed at which the aircraft are approaching each other laterally, can be based on an assumption. The hourly rate of entry into lateral overlap and $P_y(S_y)$ can be calculated from the two probability density functions (PDFs) for the lateral deviations of the aircraft on the two parallel air routes³. Given these PDFs, say $f(y)$ and $g(y)$, the

³ If aircraft 1 is modeled as moving along the line $y = 0$ with its lateral deviation and position modeled by the random variable Y_1 with PDF $f(x)$ and aircraft 2 as moving along line $y = S_y$ with its lateral deviation modeled by the random variable Y_2 with PDF, $g(x)$, and its lateral position, therefore, modeled by $Y_2 + S_y$, then the random variable $Y = Y_2 + S_y - Y_1$ will represent the lateral overlap of the two aircraft and its PDF,

$h(x)$, will be the convolution of $f(x)$ and $g(x - S_y)$. That is: $h(y) = \int_{-\infty}^{\infty} f(u)g(y - u - S_y)du$.

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PDF for their overlap is $h(y) = \int_{-\infty}^{\infty} f(u)g(y-u-S_y)du$ and the probability of overlap, $P_y(S_y)$, is therefore

$$\int_{-\lambda_y}^{\lambda_y} h(y)dy = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f(u)g(y-u-S_y)dudy \quad (A4)$$

for aircraft wingspan λ_y . Since this wingspan is small compared to the other distances in the double integral, its value, the overlap probability, can be approximated by

$$P_y(S_y) = \int_{-\lambda_y}^{\lambda_y} h(y)dy \approx 2\lambda_y \int_{-\infty}^{\infty} f(u)g(u-S_y)du. \quad (A5)$$

Combining equations (A3) and (A5), the probability of a TCV becomes

$$P(\text{TCV}) = \left| \dot{y}(S_y) \right| \int_{-\infty}^{\infty} f(u)g(u-S_y)du \quad (A6)$$

Appendix B: Johnson Distributions

The Johnson family of empirical distributions is based on transformations of a standard normal variate. An advantage of such a transformation is that estimates of the percentiles of the fitted distribution can be obtained either from a table of areas under a standard normal distribution or from a computer program which computes areas under a standard normal distribution. Another advantage is that during a Monte Carlo simulation, variates from the distribution are readily computed from the standard normal distribution. The Johnson distributions also can be fitted to the data with relative ease compared to the Pearson distributions. The Johnson distributions are divided into three families as follows:

1. The S_L family is characterized by the transformation:

$$z = \gamma + \delta \ln\left(\frac{x - \varepsilon}{\lambda}\right), \quad x > \varepsilon, \lambda > 0 \quad (B1)$$

where x is the variable to be fitted by the Johnson distribution and z is a standard normal variate. Each curve in this family is bounded on the left by ε and is unbounded on the right. By performing a certain transformation of the parameters δ and γ the curves can be converted to the log-normal distribution.

2. The S_B family is characterized by the transformation:

$$z = \gamma + \delta \ln\left(\frac{x - \varepsilon}{\lambda + \varepsilon - x}\right), \quad \varepsilon < x < \varepsilon + \lambda. \quad (B2)$$

where x is the variable to be fitted by the Johnson distribution and z is a standard normal variate. Each curve in this family is bounded on the left by ε and on the right by $\varepsilon + \lambda$. These curves resemble the Weibul or extreme-value families. The parameters γ and δ are shape parameters, ε is a location parameter, and λ is a scale parameter.

3. The S_U family is characterized by the transformation:

$$z = \gamma + \delta \sinh^{-1}\left(\frac{x - \varepsilon}{\lambda}\right), \quad -\infty < x < \infty, \lambda > 0. \quad (B3)$$

where x is the variable to be fitted by the Johnson distribution and z is a standard normal variate. Each curve in this family is unbounded and unimodal. The parameters γ and δ are shape parameters, ε is a location parameter, and λ is a scale parameter.

To use the Johnson family of curves it is necessary to invert Equations (B1), (B2), and (B3); that is, each of the equations must be solved for x .

1. The S_L transformation after inversion is:

$$x = \varepsilon + \lambda \exp\left(\frac{z - \gamma}{\delta}\right), \quad -\infty < z < \infty. \quad (B4)$$

2. The S_B transformation after inversion is:

$$x = \varepsilon + \frac{\lambda}{1 + \exp\left(\frac{\gamma - z}{\delta}\right)}, \quad -\infty < z < \infty. \quad (B5)$$

3. The S_U transformation after inversion is:

$$x = \varepsilon + \lambda \sinh\left(\frac{z - \gamma}{\delta}\right), \quad -\infty < z < \infty. \quad (B6)$$

Because the variable z in each transformation is a standard normal variate, the probability distribution of each Johnson family of curves may be determined from a normal table.

1. The Probability Density Function of a member of the Johnson S_L family has the following form:

$$f_1(x) = \frac{\delta}{(x - \varepsilon)\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\gamma + \delta \ln\left(\frac{x - \varepsilon}{\lambda}\right)\right]^2\right\}, \quad x \geq \varepsilon, \quad (B7)$$

$\delta > 0, -\infty < \gamma < \infty, \lambda > 0, -\infty < \varepsilon < \infty.$

2. The Probability Density Function of a member of the Johnson S_B family has the following form:

$$f_2(x) = \frac{\delta\lambda}{(x - \varepsilon)(\lambda - x + \varepsilon)\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\gamma + \delta \ln\left(\frac{x - \varepsilon}{\lambda - x + \varepsilon}\right)\right]^2\right\}, \quad (B8)$$

$\varepsilon < x < \varepsilon + \lambda, \delta > 0, -\infty < \gamma < \infty, \lambda > 0, -\infty < \varepsilon < \infty.$

3. The Probability Density Function of a member of the Johnson S_U family has the following form:

$$f_3(x) = \frac{\delta}{\sqrt{2\pi[(x-\varepsilon)^2 + \lambda^2]}} \exp \left[-\frac{1}{2} \left(\gamma + \delta \ln \left\{ \left(\frac{x-\varepsilon}{\lambda} \right) + \left[\left(\frac{x-\varepsilon}{\lambda} \right)^2 + 1 \right]^{1/2} \right\} \right)^2 \right], \quad (B9)$$

$-\infty < x < \infty, \delta > 0, -\infty < \gamma < \infty, \lambda > 0, -\infty < \varepsilon < \infty.$

Sampling From a Johnson Curve

After the appropriate Johnson curve has been selected and the parameters γ , δ , ε , and λ have been determined, then it is a simple matter to select random variates from the Johnson distribution. The method involves the following steps:

1. Select two random numbers r_1 and r_2 from the uniform interval (0, 1).
2. Use one of the Box-Muller equations to compute a random variate z from the standard normal distribution, $N(0, 1)$.
3. Substitute z into the appropriate Johnson transformation. If the Johnson curve is of type S_L then substitute z into Equation (B4) to obtain the random variate x . If the Johnson curve is of type S_B then substitute z into Equation (B5) to obtain the random variate x . If the Johnson curve is of type S_U then substitute z into Equation (B6) to obtain the random variate x .

Appendix C: Related Topics

C.1 MITRE Equivalent Lateral Spacing Operation Standard Report (MTR100194)

While this project was in progress, the MITRE Corporation was developing a proposed standard that would allow credits (in the form of reduced divergence requirements) for parallel departure procedure design. The approach taken considered the minimum runway separation allowed in [1] as a baseline “safe” condition and calculated reduced divergence angles for runway pairs that were either farther apart than the minimum, had staggered thresholds, or limited the departures to aircraft with enhanced navigation capabilities (such as RNAV). The reduced divergence angles still achieved greater separation between the departure tracks than the minimum separation allowed by [1] and were therefore assumed to be as safe or safer. A review of the order by Flight Standards subject matter experts found the report to be mathematically sound and the proposed standard technically feasible. Data collected at Atlanta and other locations appeared to correlate well with the material in the report (although the report did not include enough information on the data used to do a thorough comparison.) Flight Standards raised no objections to application of the method to validation of the design of the Atlanta RNAV departure procedures or to the reports inclusion as supporting material for the Safety Risk Management Document produced for the Atlanta waiver application due to both the technical soundness of the proposal and the results of this study that were available at the time.

However, all other issues aside, consideration needs to be given to the fundamental assumption of the MITRE study: that the worst case allowed by standards still achieves the acceptable level of safety so that any configuration for which the risk is no worse than the worst case is acceptable. An alternative assumption might be that the standard is expected to be applied to a range of cases and that the resultant overall risk meets an acceptable level of safety. The worst case allowed might have a higher risk than the desirable system level but it is offset by “better” cases. It is not being suggested that such an averaging process was applied to the determination of departure divergence criteria but it needs to be understood that application of this assumption will lead to an increase in total system risk. That increase may be insignificant (as it would appear to be at Atlanta based on this study) or it may not but it will be some finite quantity. Achieving a net improvement to the total system safety will require additional mitigations.

C.2 Blunder Considerations

Neither this study nor the MITRE work specifically addressed the impact of blunders in the case of simultaneous departures (significant course deviations off of the intended track). When the question was raised in the Safety Risk Management Panel, the response was that since the tracks were always further apart than the minimum allowed, then the distance a blunderer must travel is always greater. Therefore, the reduced divergence case is at least as safe as the minimum already allowed as far as the blunder scenario is concerned. The response appeared reasonable but it neglected consideration of the

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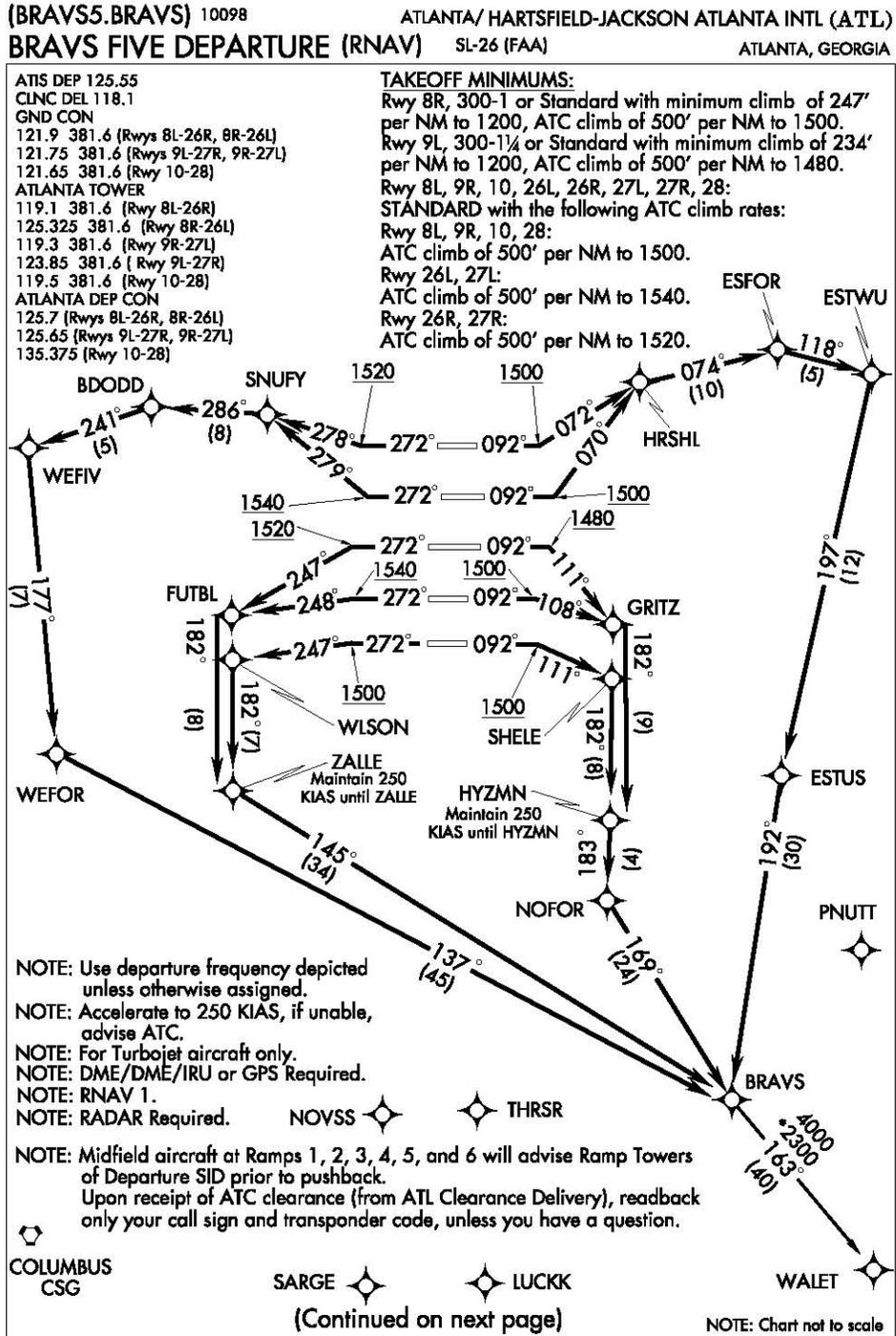
relative convergence speeds. For the same blunder angle and airspeed, an aircraft that was on an 8 degree divergence prior to the blunder will be approaching the other track faster than one that was on a 15 degree divergence. A tool was developed to compare the times it took for the faster converging aircraft to cover the greater distance (per the reduced divergence) with the slower converging aircraft travelling the minimum distance allowed by the 7110.65. The results based on the Atlanta departures and considering a range of convergence speeds showed that all of the proposed parallel departure scenarios were as safe or safer than the minimum case in the order.

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Appendix D: Sample RNAV Departure



BRAVS FIVE DEPARTURE (RNAV) ATLANTA, GEORGIA
(BRAVS5.BRAVS) 10098 ATLANTA/ HARTSFIELD-JACKSON ATLANTA INTL (ATL)

(BRAVS5.BRAVS) 07242 ATLANTA/ HARTSFIELD - JACKSON ATLANTA INTL (ATL)
BRAVS FIVE DEPARTURE (RNAV) SL-26 (FAA) ATLANTA, GEORGIA



DEPARTURE ROUTE DESCRIPTION

TAKE-OFF RWY 8L: Climb heading 092° to at or above 1500, then on 072° course to HRSHL, then via depicted route to BRAVS, thence....
TAKE-OFF RWY 8R: Climb heading 092° to at or above 1500, then on 070° course to HRSHL, then via depicted route to BRAVS, thence....
TAKE-OFF RWY 9L: Climb heading 092° to at or above 1480, then on 111° course to GRITZ, then via depicted route to BRAVS, maintain 250 KIAS until HYZMN, thence....
TAKE-OFF RWY 9R: Climb heading 092° to at or above 1500, then on 108° course to GRITZ, then via depicted route to BRAVS, maintain 250 KIAS until HYZMN, thence....
TAKE-OFF RWY 10: Climb heading 092° to at or above 1500, then on 111° course to SHELE, then via depicted route to BRAVS, maintain 250 KIAS until HYZMN, thence....
TAKE-OFF RWY 26L: Climb heading 272° to at or above 1540, then on 279° course to SNUFY, then via depicted route to BRAVS, thence....
TAKE-OFF RWY 26R: Climb heading 272° to at or above 1520, then on 278° course to SNUFY, then via depicted route to BRAVS, thence....
TAKE-OFF RWY 27L: Climb heading 272° to at or above 1540, then on 248° course to FUTBL, then via depicted route to BRAVS, maintain 250 KIAS until ZALLE, thence....
TAKE-OFF RWY 27R: Climb heading 272° to at or above 1520, then on 247° course to FUTBL, then via depicted route to BRAVS, maintain 250 KIAS until ZALLE, thence....
TAKE-OFF RWY 28: Climb heading 272° to at or above 1500, then on 247° course to WLSO, then via depicted route to BRAVS, maintain 250 KIAS until ZALLE, thence....
maintain 10,000 (or requested altitude, if lower), expect clearance to filed altitude ten minutes after departure.

WALET TRANSITION (BRAVS5.WALET):

- NOTE: Rwy 8L: Multiple trees beginning 930' from DER, 533' left of centerline, up to 58' AGL/1048' MSL. Bldg 2705' from DER, 1061' left of centerline, 72' AGL/1068' MSL.
- NOTE: Rwy 8R: Antenna on tower 4816' from DER, 1637' right of centerline, 153' AGL/1148' MSL. Tower 4804' from DER, 1666' right of centerline, 148' AGL/1145' MSL. Stack on Bldg 1734' from DER, 945' left of centerline, 47' AGL/1043' MSL.
- NOTE: Rwy 9L: Rod on pole 5306' from DER, 1731' left of centerline, 187' AGL/1137' MSL. Bush 101' from DER, 453' left of centerline, 3' AGL/981' MSL.
- NOTE: Rwy 10: Tower 4223' from DER, 400' left of centerline, 216' AGL/1135' MSL. Antenna on Tower 4240' from DER, 407' left of centerline, 217' AGL/1134' MSL. Pole 59' from DER, 467' right of centerline, 51' AGL/1016' MSL. Pole 198' from DER, 520' right of centerline, 43' AGL/1011' MSL.
- NOTE: Rwy 26L: Tree 1370' from DER, 186' left of centerline, 53' AGL/1060' MSL. Tree 2832' from DER, 564' left of centerline, 50' AGL/1097' MSL. Rod on Bldg 1249' from DER, 752' left of centerline, 52' AGL/1059' MSL. Bldg 1138' from DER, 636' left of centerline, 43' AGL/1057' MSL.
- NOTE: Rwy 26R: Multiple trees beginning 1786' from DER, 110' right of centerline, up to 83' AGL/ 1135' MSL. Multiple trees beginning 1988' from DER, 143' left of centerline, up to 100' AGL/ 1112' MSL. Pole 3196' from DER, 997' right of centerline, 49' AGL/1101' MSL. Antenna on tower 3382' from DER, 1024' right of centerline, 76' AGL/1128' MSL. Antenna 3814' from DER, 1069' right of centerline, 69' AGL/1121' MSL.
- NOTE: Rwy 27L: Hopper 3936' from DER, 1255' right of centerline, 96' AGL/1131' MSL.
- NOTE: Rwy 27R: Tree 4396' from DER, 1005' right of centerline, 92' AGL/1137' MSL. Antenna on hopper 3568' from DER, 862' right of centerline, 68' AGL/1113' MSL. Light pole 1012' from DER, 729' right of centerline, 28' AGL/1046' MSL. Multiple hoppers beginning 3680' from DER, 201' right of centerline up to 96' AGL/1131' MSL. Elevator 4001' from DER, 207' right of centerline, 103' AGL/1125' MSL.
- NOTE: Rwy 28: Catenary 2001' from DER, 771' left of centerline, 60' AGL/1051' MSL.

SE-4, 02 JUN 2011 to 30 JUN 2011

SE-4, 02 JUN 2011 to 30 JUN 2011

BRAVS FIVE DEPARTURE (RNAV) ATLANTA, GEORGIA
 (BRAVS5.BRAVS) 07242 ATLANTA/ HARTSFIELD - JACKSON ATLANTA INTL (ATL)

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