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Safety Study Report on Chicago O'Hare and Midway Operations Risk Assessment

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NOTICE

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12. Abstract

During certain weather conditions, Chicago O'Hare International (ORD) tower is forced to stagger approaches to runways 14R and 14L when approaches are being conducted to Chicago Midway (MDW) runway 13C. If the approaches are not staggered and simultaneous missed approaches occur from runways 14L and 14R at ORD, then the aircraft from runway 14R cannot be turned away from the 13C aircraft at MDW thereby causing a potential loss of required separation. Staggering approaches to runways 14R and 14L at ORD results in a reduction of the Airport Acceptance Rate (AAR) at ORD from 72 to 60 per hour. The AAR at ORD could be improved to the normal rate of 72 per hour if the approaches to 14L and 14R could be conducted independently during periods when instrument approaches are required. Independent operations can be granted if the proposed procedure will meet the FAA's established target level of safety (TLS).

An extensive computer simulation was required to determine whether the target level of safety was met. The Flight Operations Simulation and Analysis Branch (AFS-440) modified its Airspace Simulation and Analysis Tool (ASAT) computer modeling system in order to evaluate four possible scenarios that could result from independent approach operations at ORD. The probability of risk associated with independent operations to ORD runways 14L and 14R was found to be less than the target level of safety.

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EXECUTIVE SUMMARY

During certain weather conditions, Chicago O’Hare International (ORD) tower is forced to stagger aircraft on approach to runways 14R and 14L when approaches are being conducted to Chicago Midway (MDW) runway 13C. If the approaches are not staggered and simultaneous missed approaches occur from runways 14R and 14L, the aircraft from runway 14R cannot be quickly turned away from the aircraft on approach to runway 13C, thereby limiting controller options and potentially causing a loss of required aircraft separation. Staggering the aircraft on approach to 14R and 14L gives controllers more options in dealing with 14R and 14L missed approaches and the landing stream on 13C at Midway. However, this approach stagger scheme reduces the Airport Acceptance Rate (AAR) at ORD from 72 to 60 per hour. During these occasions, arrivals to MDW are virtually unrestricted. Stagger approach operations, also called dependent parallel approach operations, cause increased controller workload and, in this case, an economic hardship on the users of ORD.

It is anticipated that the AAR at ORD could be improved to the normal rate of 72 per hour if the approaches to runways 14R and 14L could be conducted independently during periods when instrument approaches are required. However, independent approaches would require a study to demonstrate if proposed operation will meet the FAA’s established target level of safety (TLS).

An extensive computer simulation was required to determine whether independent approaches to runways 14L and 14R at ORD can be conducted simultaneously with MDW runway 13C approaches and meet the TLS. The computer simulation was requested by the Operations Branch, AGL-530, of the Federal Aviation Administration (FAA) Great Lakes Regional Office and conducted by the FAA Flight Operations Simulation and Analysis Branch, AFS-440.

AFS-440 modified its Airspace Simulation and Analysis Tool (ASAT) computer modeling system to emulate geographical and aeronautical conditions peculiar to ORD and MDW. This included the precise relative location of runways, navaids such as Instrument Landing Systems (ILS), and surveillance radars. The electronic characteristics of the ILS and radars were also included in the model. AFS-440 worked closely with AGL-530 to determine four scenarios for the simulation that would emulate anticipated air traffic procedures. These four scenarios were analyzed from a safety risk standpoint using Monte Carlo techniques.

Since approaches to runways 14R and 14L must be staggered at ORD when MDW is conducting approaches to runway 13C, the primary situation of interest involves independent approaches to runways 14R and 14L with a missed approach from runway 14R while an aircraft is intercepting the localizer of the ILS of runway 13C at MDW. This situation can be resolved into four scenarios. In the first scenario, the aircraft approaching 14R performs a missed approach without a turn and with all engines operating. In the second scenario, the aircraft approaching 14R performs a missed approach without a turn and with one engine inoperative. In the third scenario, the aircraft approaching 14R performs a missed approach with a left turn after reaching 3,500 feet with all engines operating. In the fourth scenario, the aircraft approaching 14R performs a missed approach with a left turn after reaching 3,500 feet with one engine inoperative. In all four scenarios, the aircraft approaching runway 13C at MDW is vectored to intercept the localizer for runway 13C.

For each of the simulation scenarios, the test realization consisted of an aircraft performing a missed approach from ORD runway 14R while a second aircraft turned to final for MDW runway 13C. The aircraft turning to final at MDW overshoots the turn with the amount of overshoot randomly selected. In each case, the smallest separation distance of the two aircraft as they flew simulated flight tracks, called the closest point of approach (CPA), was recorded. The CPA was the slant line distance between the centers of gravity of the two aircraft. If the CPA was less than 500 feet, a test criterion violation (TCV), was said to have occurred.

For each of the four scenarios, 100,000 simulated flights were conducted and their CPAs recorded. Probability density curves were developed for each set of CPA data. The probability of a TCV occurring during a scenario was estimated from the probability density curves.

The target level of safety (TLS) is the maximum allowable probability of a collision. The target level of safety has been determined from historical data for various operations such as parallel independent instrument approaches. The most recent accident data was examined, along with departure rates, to determine the accident rate during ILS approaches. This rate was used to determine the rate that accidents could be allowed to occur and not increase the current overall ILS approach accident rate. The TLS was found to be 4×10^{-8}, or 1 accident per 25 million approaches.

The risk associated with scenario 1 was found to be 1.6×10^{-9}. The risk associated with scenario 2 was found to be 2.6×10^{-14}. The risk associated with scenario 3 was found to be 2.1×10^{-8}. The risk associated with scenario 4 was found to be 2.7×10^{-13}. However, during approach operations to ORD runways 14R and 14L and MDW runway 13C, a TCV could be caused by the occurrence of any one of the four scenarios. Thus, the total probability or risk associated with approach operations to ORD runways 14R and 14L and MDW 13C is the sum of the risks associated with each of the scenarios. The total risk was found to be 2.3×10^{-8}. The probability or risk associated with approach operations to ORD runways 14R and 14L and MDW 13C is less than the target level of safety.

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1.0. Introduction

During certain weather conditions, Chicago O'Hare International (ORD) tower is forced to stagger aircraft on approach to runways 14R and 14L when approaches are being conducted to Chicago Midway (MDW) runway 13C. If the approaches are not staggered and simultaneous missed approaches occur from runways 14R and 14L, the aircraft from runway 14R cannot be quickly turned away from the aircraft on approach to runway 13C thereby limiting controller options and potentially, causing a loss of required aircraft separation. Staggering the aircraft on approach to 14R and 14L gives controllers more options in dealing with 14R and 14L missed approaches and the landing stream on 13C at Midway. However, this approach stagger scheme reduces the Airport Acceptance Rate (AAR) at ORD from 72 to 60 per hour. During these occasions, arrivals to MDW are virtually unrestricted. Stagger approach operations, also called dependent parallel approach operations, cause increased controller workload and, in this case, an economic hardship on the users of ORD.

It is anticipated that the AAR at ORD could be improved to the normal rate of 72 per hour if the approaches to runways 14R and 14L could be conducted independently during periods when instrument approaches are required. However, independent approaches would require a study to demonstrate that the proposed operation will meet the FAA's established target level of safety (TLS).

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AFS-440 modified its Airspace Simulation and Analysis Tool (ASAT) computer modeling system to emulate geographical and aeronautical conditions peculiar to ORD and MDW. This included the precise relative location of runways, navaids such as Instrument Landing Systems (ILS), and surveillance radars. The electronic characteristics of the ILS and radars were also included in the model. AFS-440 worked closely with AGL-530 to determine four scenarios for the simulation that would emulate anticipated air traffic procedures. These four scenarios were analyzed from a safety risk standpoint using Monte Carlo techniques.

2.0. Description of the Model

2.1. Airspace Simulation and Analysis Tool (ASAT)

The primary analysis tool for this safety evaluation is ASAT. ASAT is a multifaceted, highly adaptable, computer-based tool for aviation related simulations and safety evaluations. ASAT consists of high fidelity models and in some cases, empirical data representing the following major components of a typical real world operational aviation scenario:

a. At the heart of the system are high fidelity engineering flight dynamics models of actual aircraft obtained through various government/industry partnerships. Model definition and performance is also enhanced and tailored by empirical data collected in flight simulators and flight tests.

Aircraft avionics are modeled based on requirements of the particular scenario. ASAT can model a broad range of advanced navigation systems such as Flight Management System (FMS), Global Positioning System (GPS), and Required Navigation Performance (RNP) as well as older navigation systems such as ILS, Microwave Landing System (MLS), and Distance Measuring Equipment (DME).

b. ASAT has access to a wide range of environmental models including temperature, atmospheric pressure, and wind profiles, both lateral and vertical. The aerodynamic flight models described above respond to the ASAT generated atmosphere around them in the same manner as actual aircraft do. In addition, ASAT contains an advanced aircraft wake vortex model which can generate and track wake vortices and identify encounters between wake vortices and scenario "aircraft."

c. The environment in which ASAT scenarios are run is further defined by official FAA databases providing precise geographic locations of airports, runways, navaids, routes, fixes, waypoints, and other facilities, such as radar site locations. In addition, ASAT incorporates the FAA's obstacle and terrain database for use in obstacle clearance studies.

d. Air traffic equipment impacts on scenarios are based on computer models of radar systems using manufacturer and government provided specifications. When and where necessary, the human factors contribution of air traffic controllers is measured during simulations and from this data, statistical distributions of controller response times can be determined and made available to ASAT.

Once the scenario(s) of interest are defined and the components above statistically characterized, ASAT can perform many thousands of runs in a Monte Carlo type simulation. ASAT is also capable of statistically analyzing the results of the Monte Carlo simulation. The ultimate objective of the ASAT analysis, as it was in this study, is generally a level of safety determination for the proposed operations, which can then be compared to some Target Level of Safety.

2.1.1. ASAT Main Customized Display

Due to the unique nature of the problem under investigation, ASAT was customized for this analysis. Figure 1 depicts the main initial customized display. The customized display is divided into two basic sections. The right side of the display is dedicated to visual presentation of the geographic situation with the ORD runway complex shown in the upper left, and MDW and its runways shown in the lower right hand portion. This side of the display will also show ASAT graphic output. The left side of the display is used for displaying numerical output and for controlling the various parameters defining the model scenarios.

Two other useful features can be seen in Figure 1. The long narrow rectangular feature lying between the two airports is a user defined No Transgression Zone (NTZ). This allows definition of a NTZ to ensure adequate separation of aircraft. The other feature of note is the long line to the southwest of the NTZ (the ASAT screen is oriented North to the top). This line represents a "tile" in space from which aircraft on approach to MDW will emanate during the simulation runs.

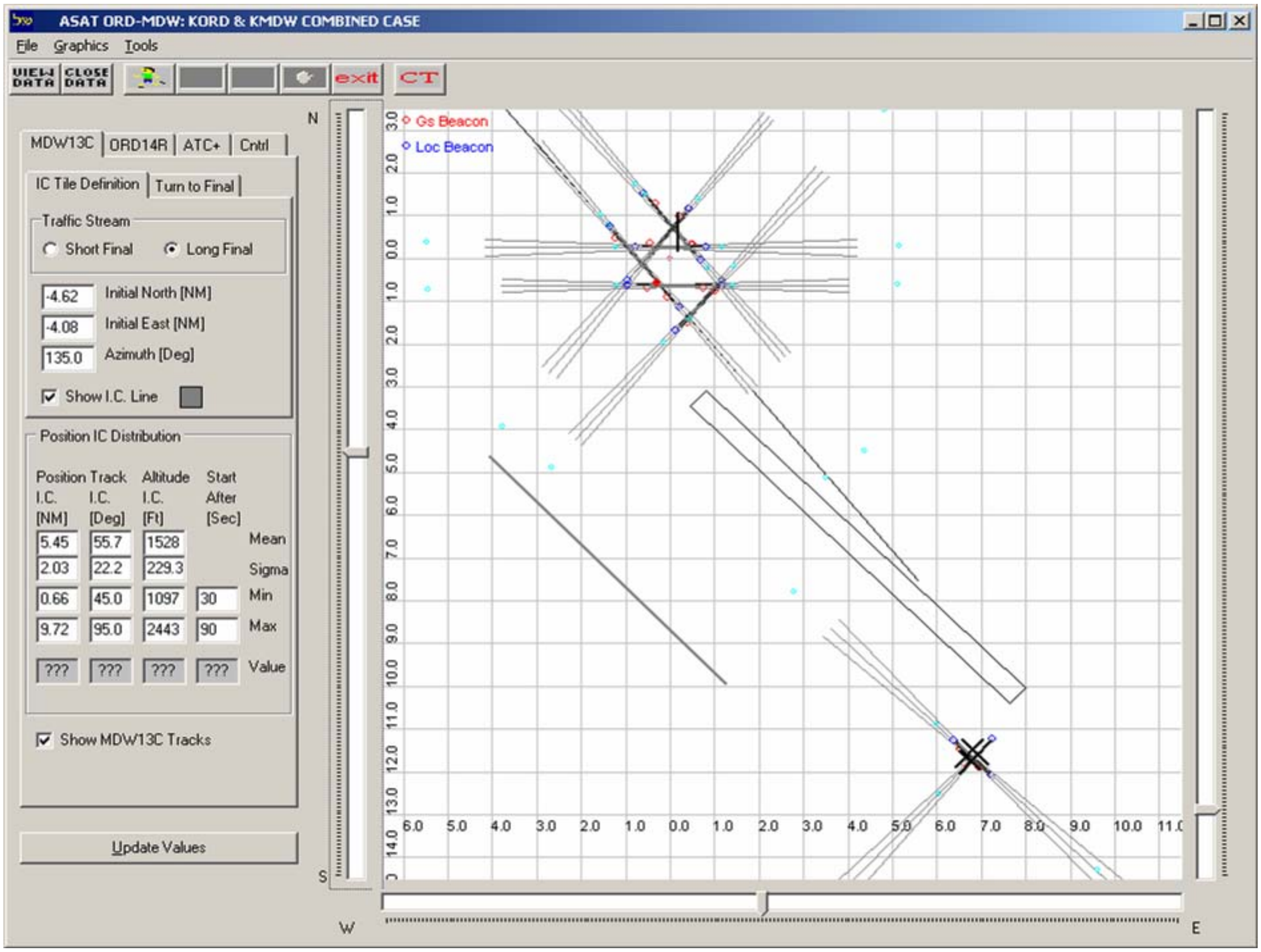

Figure 1. Main ASAT Customized Display

2.1.2. Description of ASAT Scenarios

The primary operational situation of interest consists of an aircraft executing a missed approach to runway 14R at ORD, while runway 14L at ORD is conducting independent approaches and MDW is landing runway 13C. On any given approach, controllers wanted the option of either a straight ahead or turning missed approach on ORD runway 14R. Therefore, for purposes of this analysis, the operational situation was divided into four scenarios. With reference to Table 1, these four scenarios are described below.

Scenario 1. The ORD 14R aircraft is performing a straight ahead climbing missed approach with all engines operating. As in all four scenarios, the MDW 13C aircraft fails to perform the ATC directed turn onto final approach. Given variations in aircraft starting locations at ORD and MDW and variations in controller response times, the ASAT simulations will analyze the probability of a near collision. Figure 2 shows scenario 1 graphically on an ASAT display.

Scenario Number	**O'Hare Runway 14R**			**Midway Runway 13C**	
	Procedure	Mode	Engine Out	Procedure	Mode
1	Missed Approach	No Turn	NO	Land	Vectored (misses final turn)
2			YES		
3		Turn @ 3500Ft	NO		
4			YES		

Table 1. Description of Scenarios

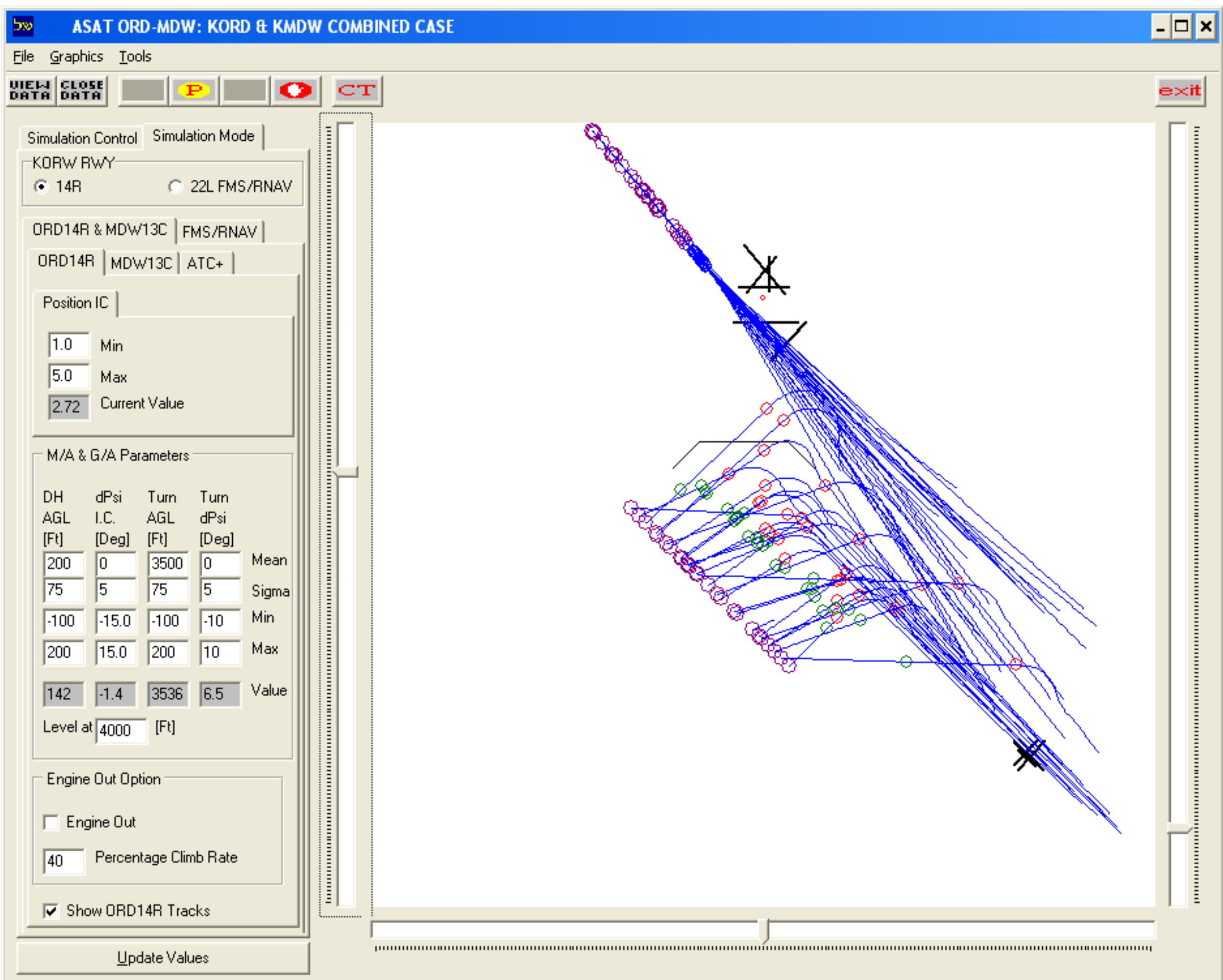

Figure 2. ASAT Graphic Depiction of Scenario 1

Scenario 2. The ORD 14R aircraft is performing a straight ahead climbing missed approach with an engine inoperative. Again, the MDW 13C aircraft fails to perform the ATC directed turn onto final approach. Figure 3 shows scenario 2 graphically displayed on an ASAT display. Note in Figure 3 that the engine out switch is turned ON.

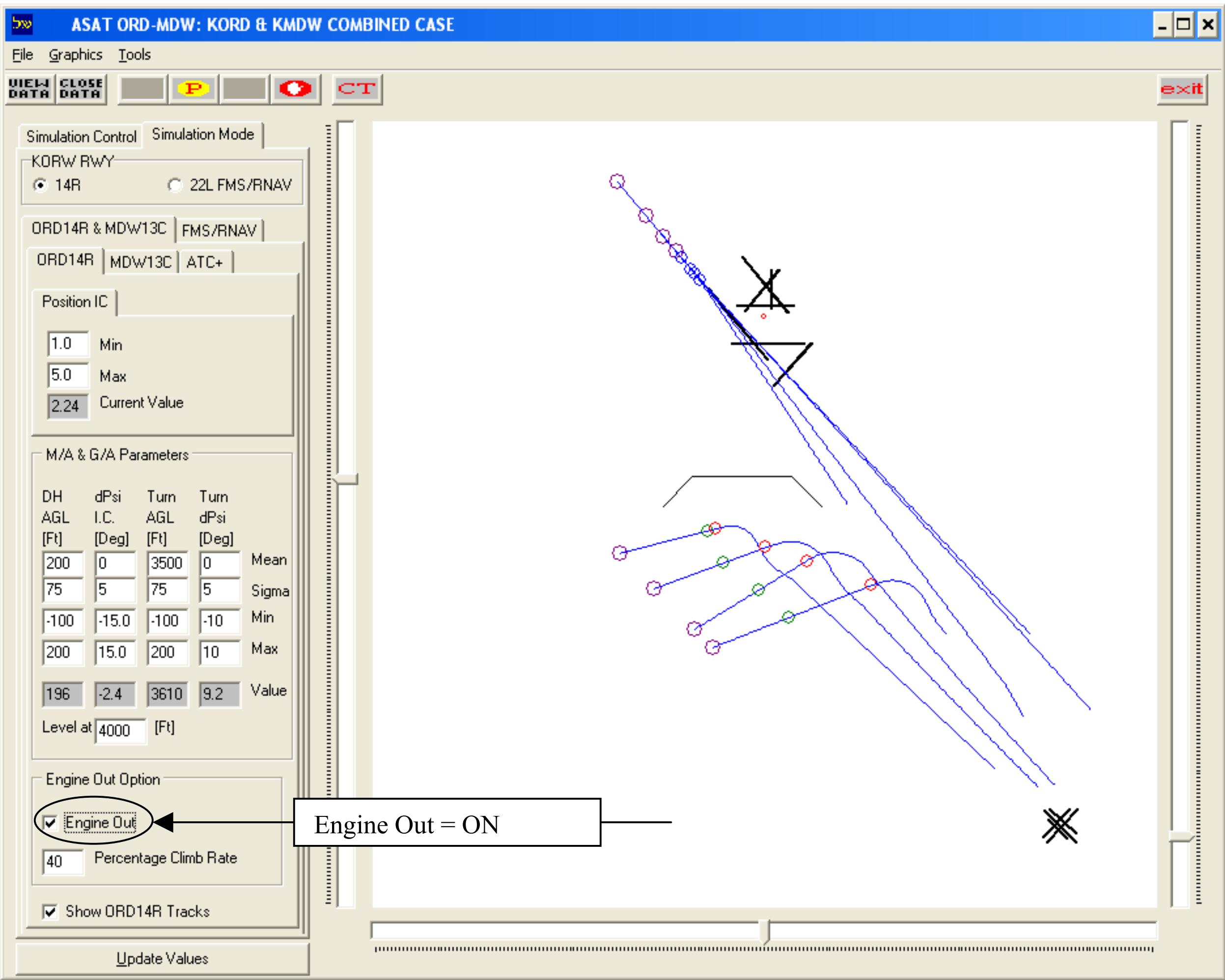

Figure 3. ASAT Graphic Depiction of Scenario 2

Scenario 3. The ORD 14R aircraft is performing a missed approach with the following instructions: climb runway heading to 3,500' Above Ground Level (AGL) then left turn to heading 095°. In this scenario, all engines are operating. As before, the MDW 13C aircraft fails to perform the ATC directed turn onto final approach. Figure 4 shows scenario 3 graphically displayed on an ASAT display. Notice in Figure 4, that the ASAT Missed Approach (M/A) and Go Around (G/A) parameters have been set for a 45° left turn at 3,500' AGL.

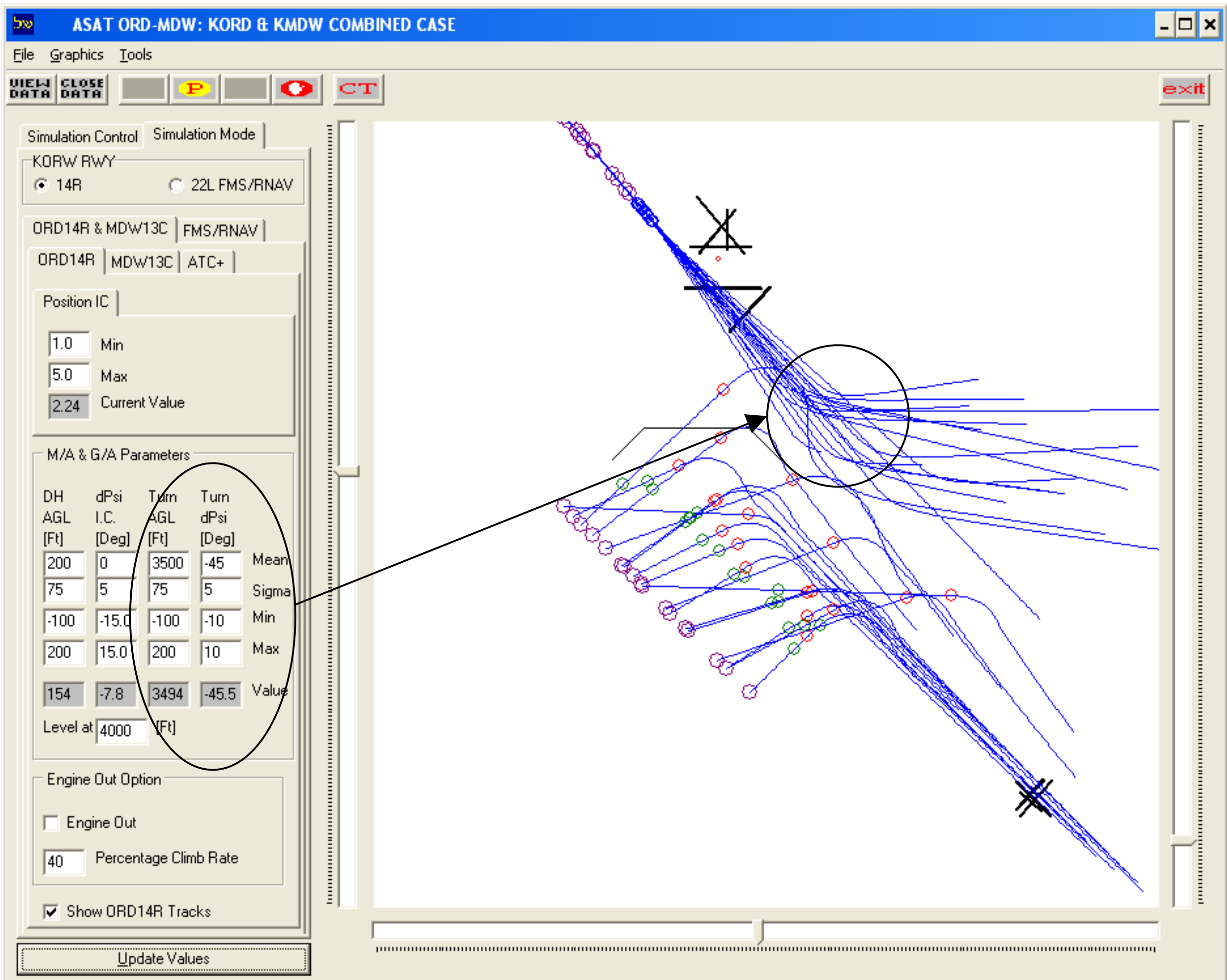

Figure 4. ASAT Graphic Depiction of Scenario 3

Scenario 4. The ORD 14R aircraft is performing a missed approach with the following instructions: climb runway heading to 3,500' AGL then left turn to heading 095°. In this scenario, one engine is inoperative. As in all previous scenarios, the MDW 13C aircraft fails to perform the ATC directed turn onto final approach. Figure 5 shows scenario 4 graphically displayed on an ASAT display. Note the longer distanced traveled compared to scenario 3 before the turn is initiated, due to poorer climb performance with engine out.

2.1.3. Control of Statistical Parameters

ASAT allows the operator to control various critical parameters, which determine the manner a given procedure is executed. In this study, different scenario control parameters were needed in order to control both the ORD 14R and MDW 13C aircraft. The following sections outline these control parameters and show the ASAT interface for exercising control.

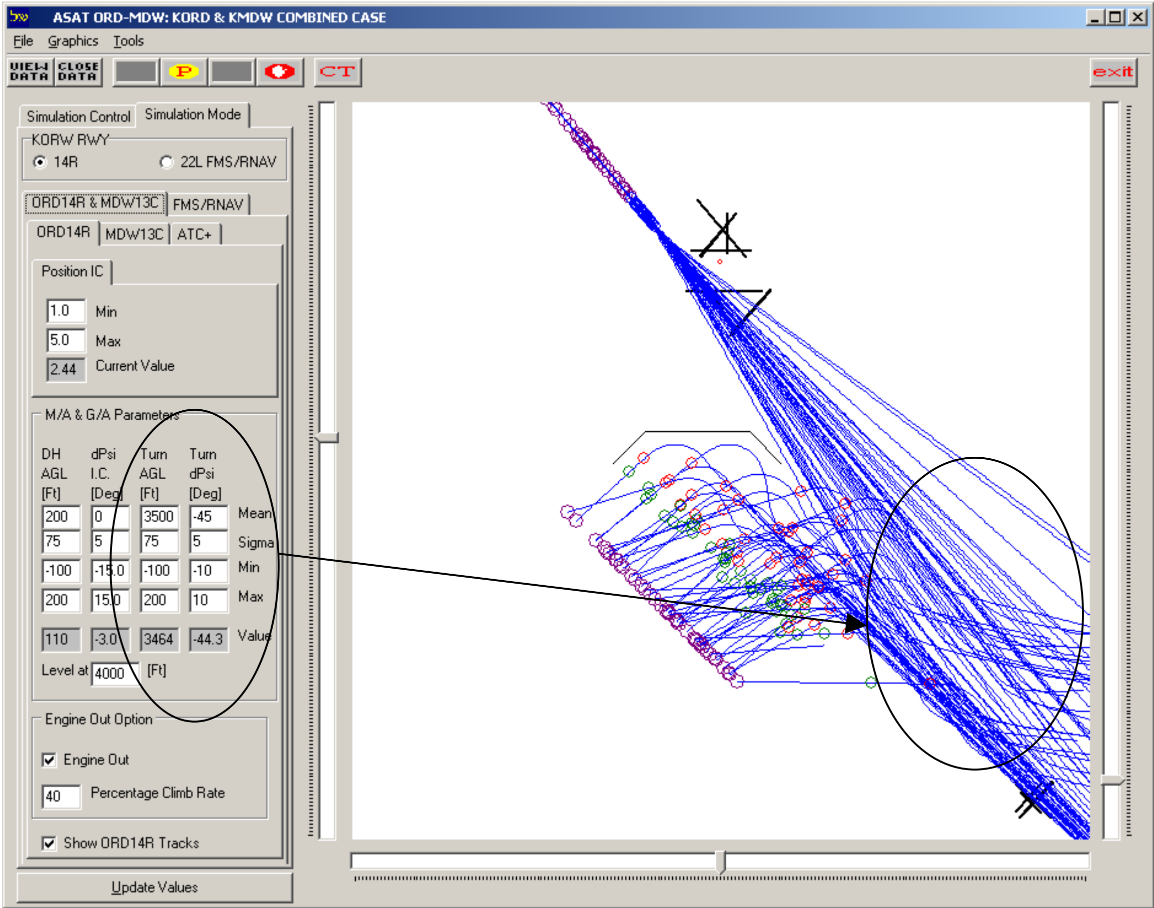

Figure 5. ASAT Graphic Depiction of Scenario 4

2.1.3.1. ORD Runway 14R Control Parameters

The following parameters (refer to Figure 6) were used by ASAT to control the tracks simulating the go around at Chicago O'Hare runway 14R:

"Position IC:" This variable determines how far from the threshold of runway 14R the aircraft is positioned at the beginning of the simulation run.

"DH AGL:" This variable determines the height above ground at which the missed approach starts.

"dPsi I.C:" This variable determines the ground track deviation during the initial climb phase of the go around prior to the first turn.

"Turn AGL:" This variable determines the height above ground at which the first turn is initiated during the go around.

"Turn dPsi:" This variable determines the amount of turn performed during the first turn of the go around.

"Engine Out:" This switch determines if the tracks will be generated under "Engine Out" conditions. If this switch is set, the climb performance of the aircraft executing a go around is degraded and will be set to the product of the nominal climb performance (non engine out) and the value entered at the "Percentage Climb Rate" field (default=40%).

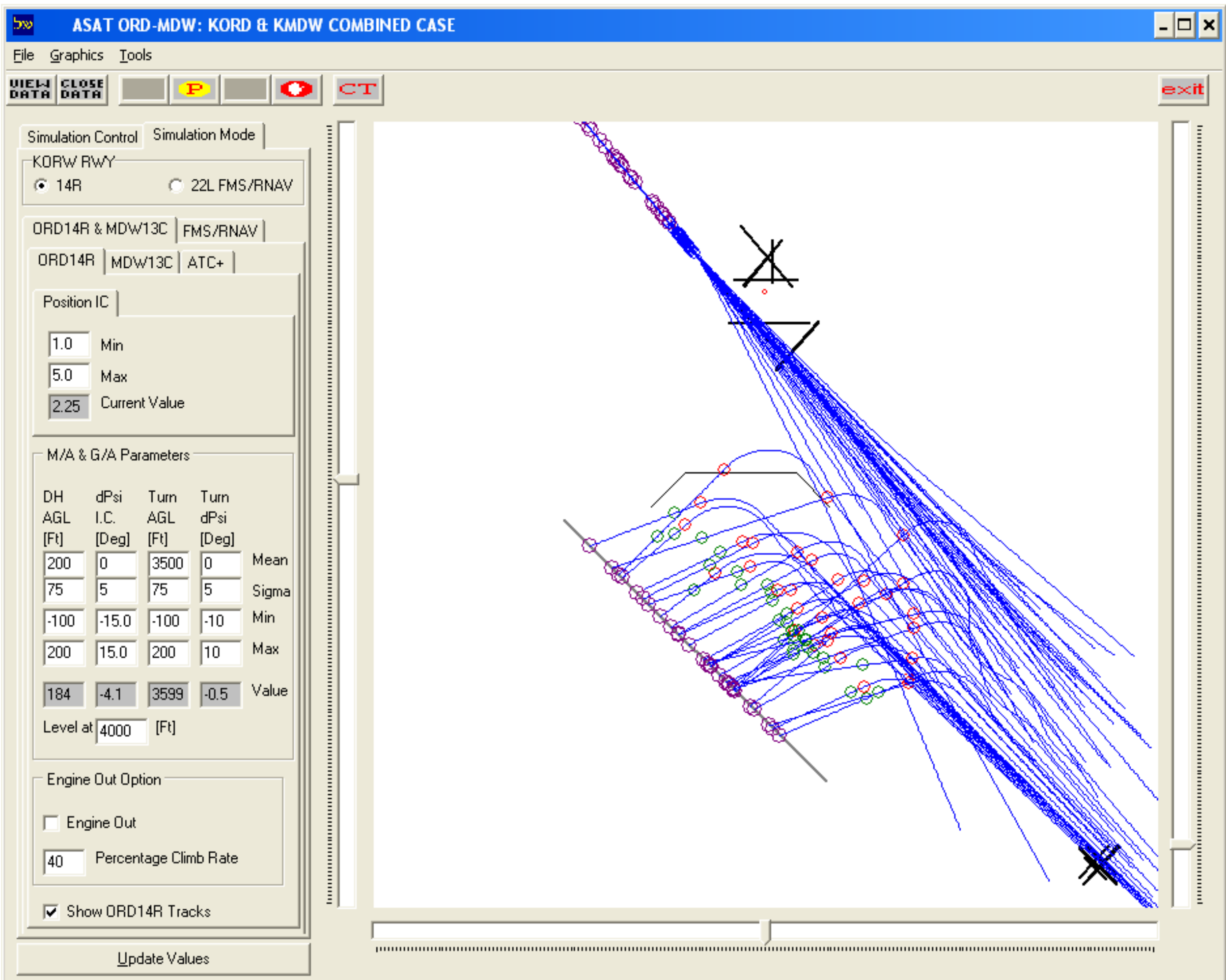

Figure 6. Control Parameters for ORD Runway 14R

2.1.3.2. MDW Runway 13C Control Parameters

The following parameters were used by ASAT to control the tracks simulating the aircraft vectored to final approach at MDW runway 13C:

"IC Tile Definition:" This set of variables defines the location and orientation of the imaginary tile from where tracks of flights into Chicago Midway runway 13C will be initiated (see Figure 7).

"Position IC Distribution:" This section contains four controls that allow the operator the flexibility to select the following initial conditions related parameters associated with the tile defined above (see Figure 7):

a. "Position I.C:" Determines the distribution across the IC tile of the position of the aircraft at simulation initialization.

b. "Track I.C:" Determines the distribution across the IC tile of the ground track of the aircraft at simulation initialization.

c. "Altitude I.C:" Determines the distribution across the IC tile of the altitude of the aircraft at simulation initialization.

d. "Start After:" Determines the time differential between the simulation start of the track approaching to Chicago O'Hare runway 14R and the simulation start of the track approaching to Chicago Midway runway 13C.

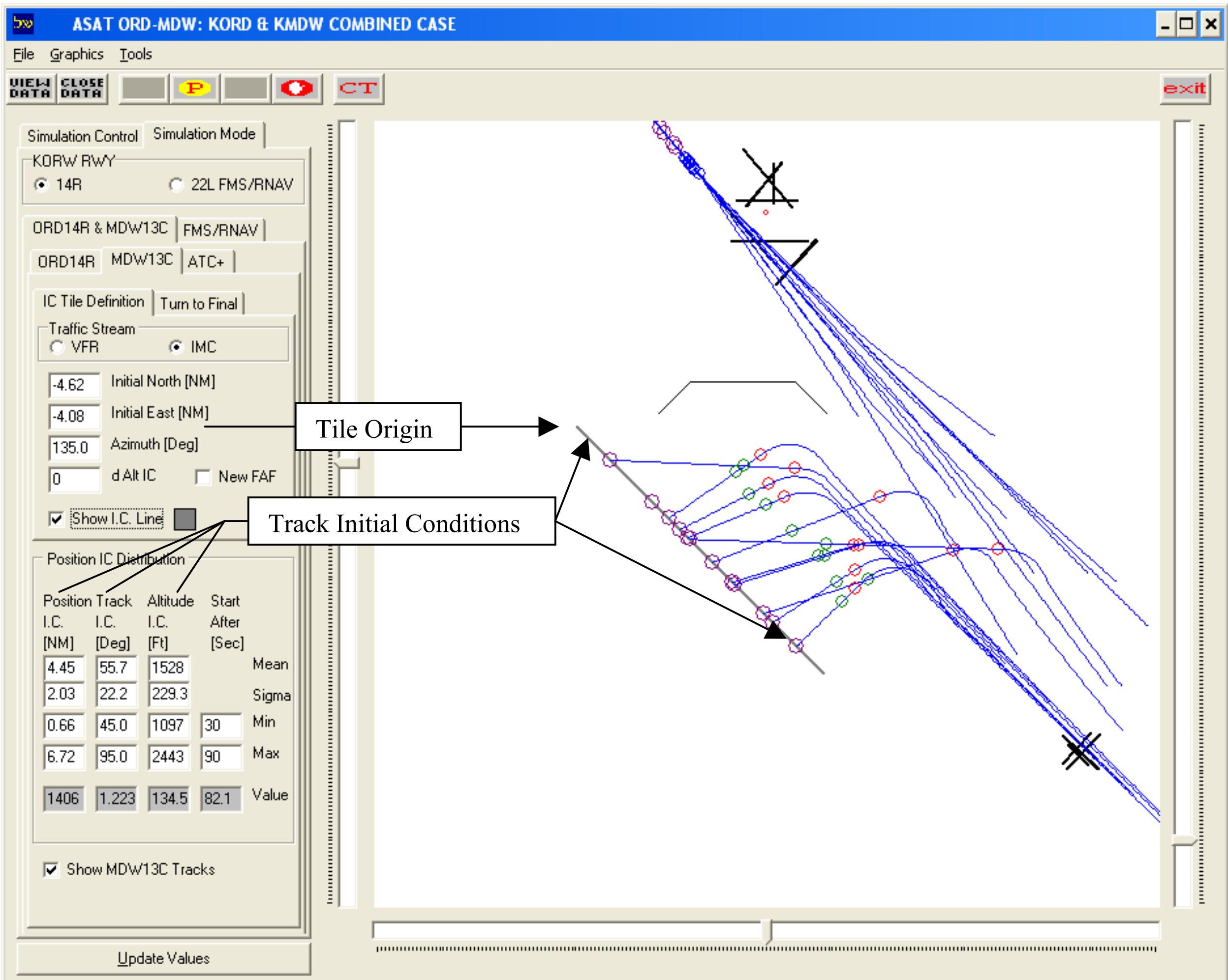

Figure 7. Initial Condition Control Parameters for MDW Runway 13C

"Turn to Final" tab (refer to Figure 8) contains variables that determine the overshoot or undershoot value during the turn to intercept the localizer. The size of the variation is controlled by the following parameters:

a. "Miss Min [NM]:" the lower end (or undershoot) in nautical miles. This value determines how early the turn will be initiated (undershoot) relative to the localizer centerline.

b. "Miss Max [NM]:" the upper end (or overshoot) in nautical miles. This value determines how late the turn will be initiated (overshoot) relative to the theoretical localizer centerline.

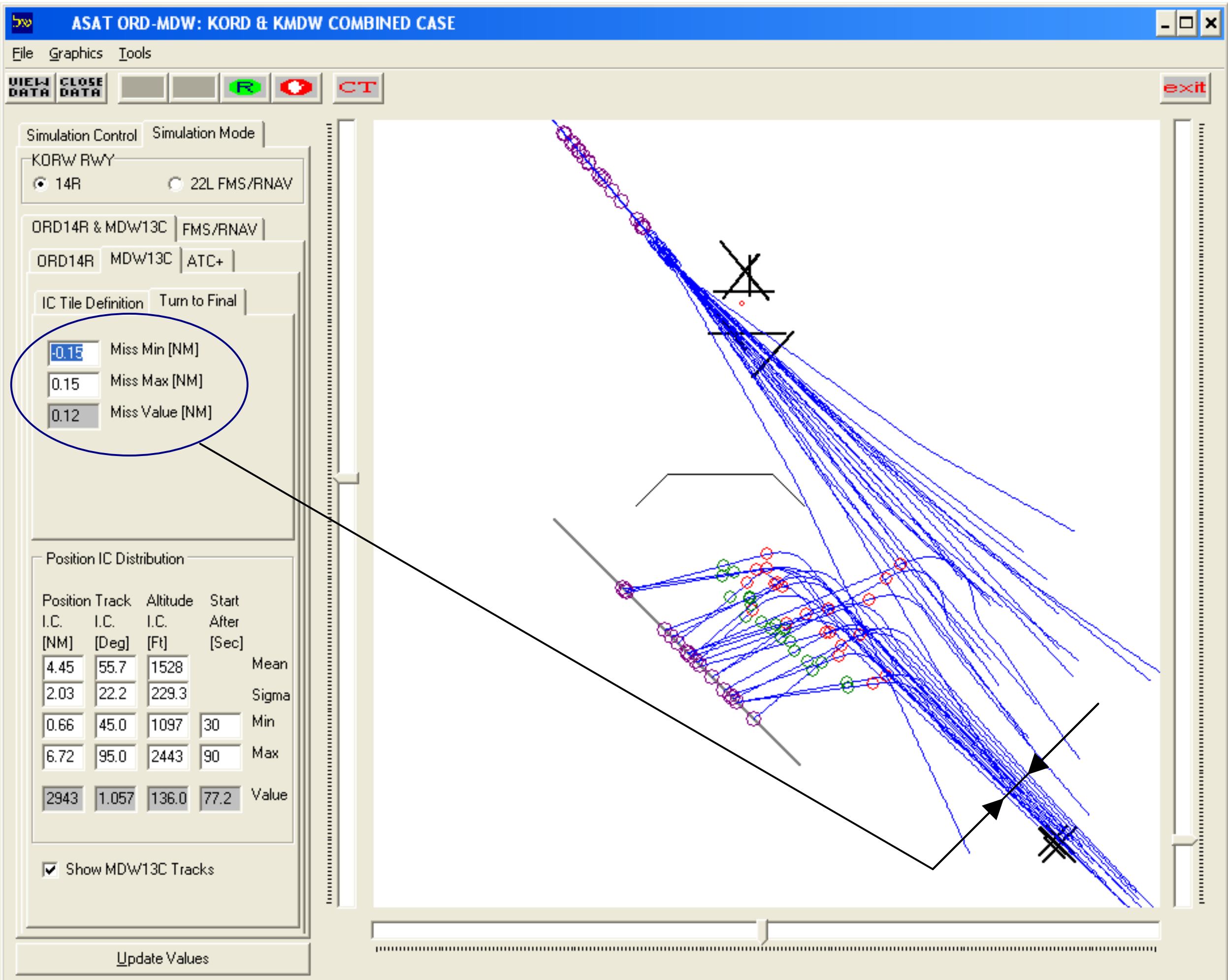

Figure 8. Turn to Final Control Parameters for MDW Runway 13C

2.2. MDW Runway 13C Radar Track Analysis

In order to accurately model the operation at MDW, a realistic representation of the dispersion of aircraft tracks under radar vector control approaching from the southwest for landing on runway 13C was essential. Again, ASAT was modified for this purpose. A software module for ATC radar tracks visualization and statistical analysis of those radar tracks was developed (see reference 3).

Using the software module mentioned above, the purpose of this analysis was to generate a distribution of tracks initial position to be used to initiate the location of aircraft approaching runway 13C at MDW during the full ASAT simulation. Specifically, a statistical characterization of the following three parameters was necessary:

a. Location of aircraft as it crosses a user defined section across the stream of traffic on the base leg of the approach. This is called the initial point for an individual aircraft.

b. Altitude of the aircraft at the initial point.

c. Ground track of the aircraft at the initial point.

The parameters of interest described above were generated with respect to an ASAT user defined cross section. Figure 9 shows this process using the modified software program.

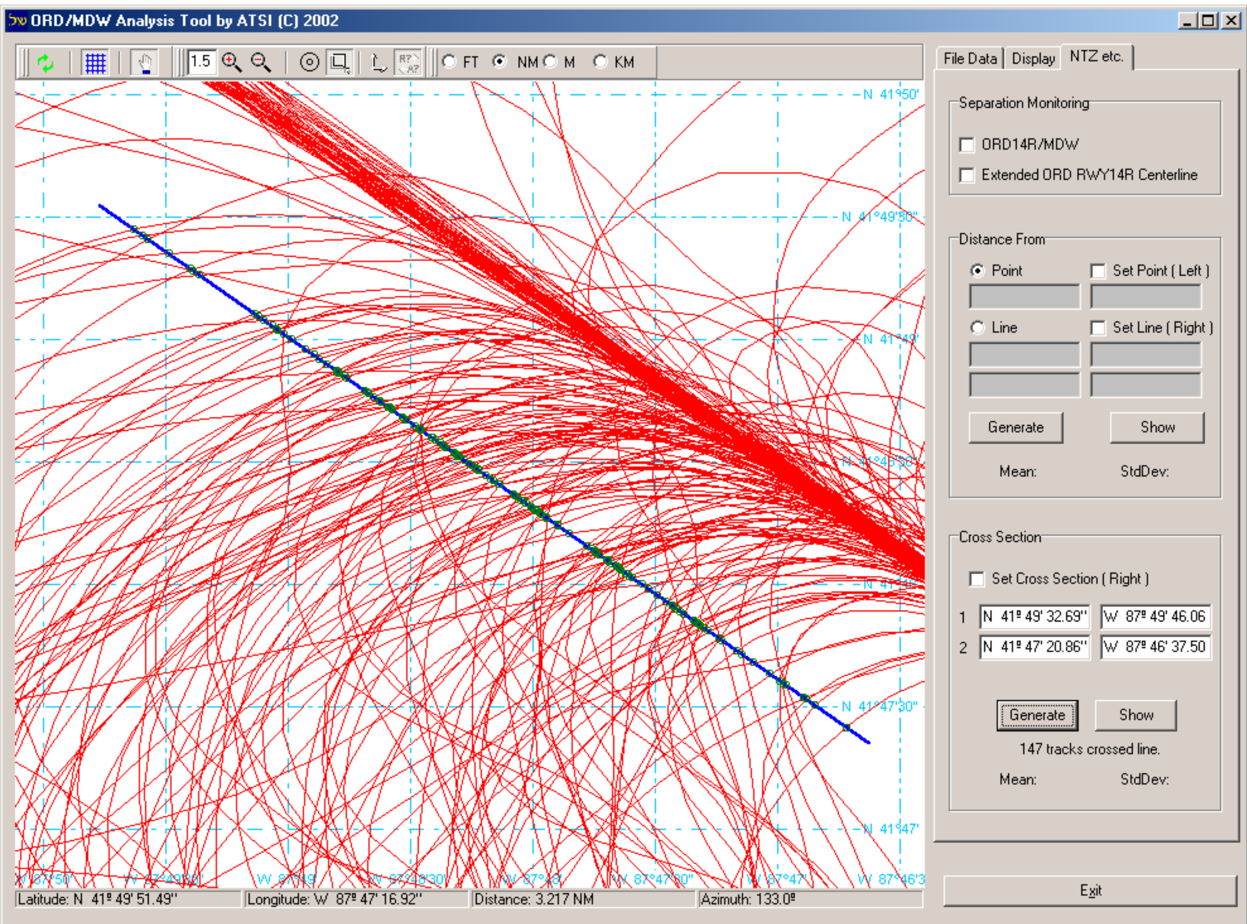

Figure 9. Generating a Cross Section of Radar Tracks

Displayed in red in Figure 9 is a multitude of actual radar tracks approaching MDW from the southwest. The cross section, shown as a long blue line in Figure 9, is defined by using the control windows located in the bottom right of Figure 9. As Figure 9 shows, 147 tracks crossed the two-dimensional cross section.

The user is also able to visualize the cross section from an "end view" perspective as shown in Figure 10. Left to right in Figure 10 is the horizontal distance along the cross section, while bottom to top is the vertical distance or altitude of the aircraft as it passes the cross section.

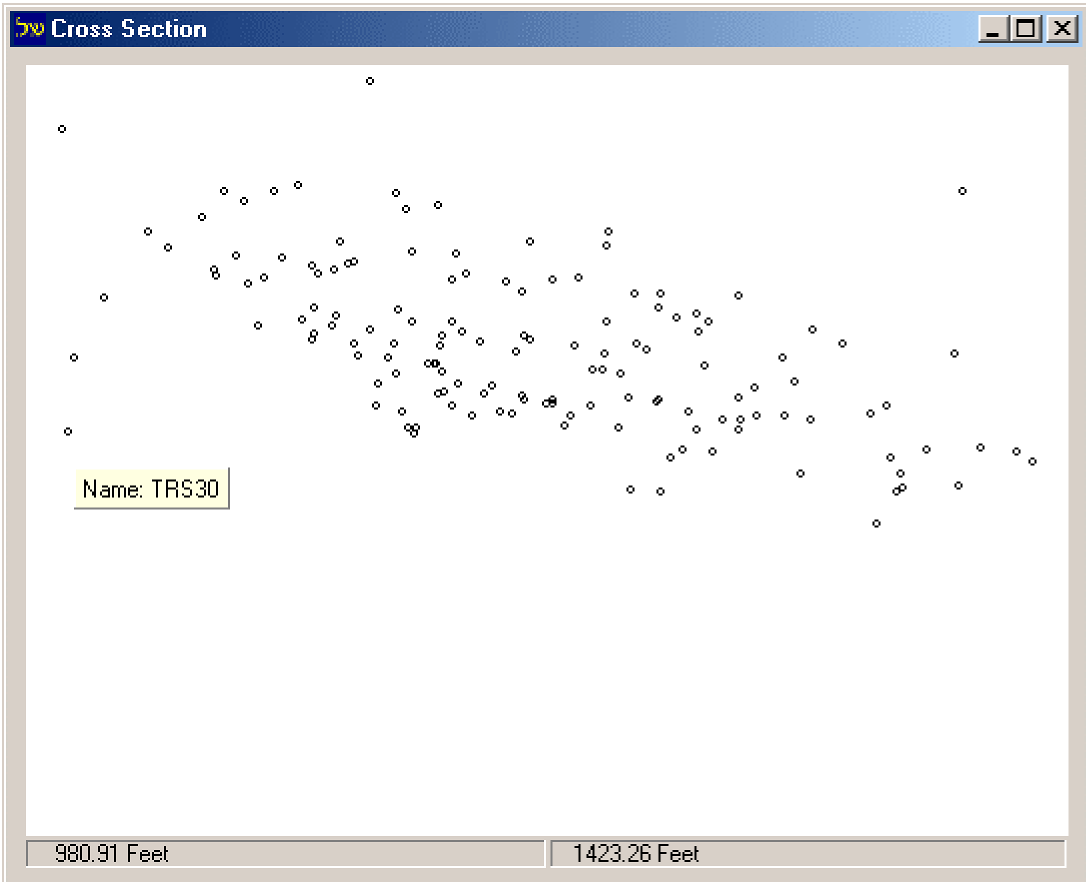

Figure 10. End View of Cross Section

The three parameters of interest as described above were statistically analyzed with respect to the cross section shown in Figure 9. The results of that analysis are summarized in Table 2. Point 1, as used in column 1 of Table 2, refers to the starting point of the cross section. One hundred forty six tracks are represented in the analysis.

Distance from Point 1 [NM]		Altitude [Ft]		Ground Track [Deg]	
Mean	5.4537894	Mean	1527.9555	Mean	55.745958
Standard Error	0.1684826	Standard Error	18.975261	Standard Error	1.840332
Median	5.5010975	Median	1494.3433	Median	60.877812
Standard Deviation	2.035783	Standard Deviation	229.27895	Standard Deviation	22.236817
Sample Variance	4.1444123	Sample Variance	52568.838	Sample Variance	494.47601
Kurtosis	-0.5266627	Kurtosis	1.833716	Kurtosis	1.3621788
Skewness	-0.1803768	Skewness	0.9692783	Skewness	-1.0648477
Range	9.0605029	Range	1345.2625	Range	123.16813
Minimum	0.6663371	Minimum	1097.4926	Minimum	-16.427795
Maximum	9.72684	Maximum	2442.7551	Maximum	106.74033
Sum	796.25325	Sum	223081.51	Sum	8138.9098
Count	146	Count	146	Count	146
Confidence Level (95.0%)	0.332999	Confidence Level (95.0%)	37.503832	Confidence Level (95.0%)	3.6373414

Table 2. Summary of Statistical Analysis of Radar Tracks

2.3. Air Traffic Controller Human Factors Analysis

Since both the landing aircraft at MDW and the ORD aircraft on missed approach are under active air traffic control, the ability of air traffic controllers to react to the four operational scenarios and respond appropriately is of critical concern to this evaluation. In order to establish realistic controller response times to the various operational scenarios, a real time simulation test was carried out at the Elgin Terminal Radar Approach Control (TRACON) training facility near Chicago on October 11, 2002. (For a more detailed description of this test, see reference 4.) The controllers that participated in the test were selected by the facility managers in coordination with National Air Traffic Controllers Association (NATCA) representatives.

The basic setup of the test was as follows:

a. A qualified ORD TRACON controller was positioned at an active ATC display within the training facility. The display contained a current depiction of the ORD/MDW airspace.

b. Two participants acted as simulated aircraft pilots. One simulated aircraft was on approach to ORD runway 14R, and the other was being vectored by the test controller to the MDW runway 13C final approach.

c. A test manager (and assistants) was on hand to control the test and log results.

The test controllers were given a familiar ORD/MDW traffic scenario, i.e. ORD landing runways 14L and 14R and MDW landing 13C. Aircraft at both ORD and MDW were provided radar vectors to the respective final approach courses, generally the localizer final approach course. At the test manager's command and unbeknownst to the controller, the pilot established on the ORD 14R approach was to execute a missed approach, while the pilot approaching to land at MDW was to ignore the controller's instruction to turn and intercept the runway 13C localizer.

Using inaudible stop watches, the test manager and his two assistances measured the time elapsed since the instruction was given to the MDW aircraft to turn and intercept the localizer (which the aircraft ignored), and the point at which the controller recognized the situation and issued new instructions.

Twenty-four controller response time data points were obtained from eight ATC simulation sessions conducted during a complete day shift. The individual response times are shown in Table 3.

Test #	Response Time (sec.)	Test #	Response Time (sec.)
1	102	13	40
2	44	14	46
3	76	15	42
4	150	16	33
5	58	17	34
6	30	18	60
7	96	19	47
8	29	20	37
9	32	21	150
10	33	22	27
11	32	23	26
12	41	24	23

Table 3. Controller Response Time – Raw Data Values

For use in the overall ASAT simulation, an analysis was performed on the data shown in Table 3 to determine a best-fit probability density function (PDF). The best-fit PDF was found to be a Johnson Type S-B with parameters as shown in Table 4.

Gamma:	0.2512951037E+01
Delta:	0.9917179819E+00
Lambda:	0.2455625124E+03
Xi:	0.1997190937E+02

Table 4. Controller Response Time – Johnson Type S-B Parameters

2.4. ASAT Monte Carlo Simulation Methodology

For each of the four simulation scenarios, the test realization consisted of an aircraft performing a missed approach from ORD runway 14R while a second aircraft turned to final for MDW runway 13C. Variation was introduced into the scenarios by statistically varying the following parameters: starting positions of each aircraft, flight paths of each aircraft, and amount of final approach course overshoot by the MDW 13C aircraft due to differences in controller response times. In each ASAT simulation run, the smallest separation distance of the two aircraft as they flew simulated flight tracks, called the closest point of approach (CPA), was recorded. The CPA was the slant line distance between the centers of gravity of the two aircraft. If the CPA was less than 500 feet, a test criterion violation (TCV), was said to have occurred.

For each of the four scenarios, 100,000 simulated flights were conducted and their CPAs recorded. Probability density curves were developed for each set of CPA data. The probability of a TCV occurring during a scenario was estimated from the probability density curves. While the occurrence of a TCV does not guarantee a collision of the simulated aircraft, a CPA of less than 500 has been deemed unacceptable in previous aviation safety studies such as reference 9.

3.0. Summary of Data Analysis and Risk Evaluation

3.1. ASAT Runs Data Analysis

Probability density functions were developed for each set of CPA data. The probability of a TCV occurring during a scenario was estimated from the associated PDFs. The probability of a CPA being less than or equal to 500 FT is found by mathematically determining the area under the curve for CPAs less than or equal to 500 FT. By letting X represent the value of a CPA, the probability is found from the equation:

$$P(X \leq 500) = \int_{-\infty}^{500} f(x)dx \qquad (1)$$

The function $f(x)$ represents the PDF. The PDFs for each scenario were modeled as Johnson S-B functions with parameters as shown in Tables 5 through 8.

Type:	Johnson S-B
Gamma:	0.1845874243D+00
Delta:	01070159533D+01
Lambda:	0.5495983194D+05
Xi:	-0.6225037885D+03

Table 5. Scenario 1 – TCV Probability Density Function Parameters

Type:	Johnson S-B
Gamma:	0.6494422326D-01
Delta:	0.9761978346D+00
Lambda:	0.5405247451D+05
Xi:	-0.1295074405D+04

Table 6. Scenario 2 – TCV Probability Density Function Parameters

Type:	Johnson S-B
Gamma:	0.3013384115D-02
Delta:	0.1133529515D+01
Lambda:	0.5575045796D+05
Xi:	-0.1295064547D+04

Table 7. Scenario 3 – TCV Probability Density Function Parameters

Type:	Johnson S-B
Gamma:	0.5767154963D-01
Delta:	0.9849846598D+00
Lambda:	0.5420978601D+05
Xi:	-0.1383735418D+04

Table 8. Scenario 4 – TCV Probability Density Function Parameters

3.2. Target Level of Safety

The target level of safety is the maximum allowable probability of a collision. The target level of safety has been determined from historical data for various operations such as parallel independent instrument approaches. The most recent accident data was examined, along with departure rates, to determine the accident rate during ILS approaches. This rate was used to determine the rate that accidents could be allowed to occur and not increase the current overall ILS approach accident rate. The TLS was found to be 4×10^{-8} per approach, or 1 accident per 25 million approaches (see paragraph 8.1 of reference 9).

3.3. Analysis of Risk Associated with Scenario 1

The probabilities found from equation 1 do not completely describe the probability or risk associated with each of the four scenarios. The probabilities found using equation 1 are conditional probabilities. Each scenario assumes that a missed approach is performed from ORD runway 14R and, almost simultaneously, an aircraft overshoots the turn to final. Probabilities computed from equation 1 assume that at least two independent events have occurred: i.e., a missed approach from ORD runway 14R and an overshoot of the turn to final to MDW runway 13C. In scenario 1, three events have to occur, a missed approach from ORD runway 14R, a missed approach from ORD runway 14L, and an overshoot of the turn to final to MDW runway 13C. In scenario 1, the missed approach from ORD runway 14R is unable to turn because of the missed approach from ORD runway 14L.

Suppose that the event "missed approach from ORD runway 14R" is denoted M14R, the event "missed approach from ORD runway 14L" is denoted by M14L, and the event "overshoot the approach to MDW runway 13C" is denoted by O13C, then the probability of a TCV caused by the conditions related to scenario 1 is given by the following probability equation.

$$\begin{aligned} P(TCV) &= P(TCV \cap M14R \cap M14L \cap O13C) \\ &= P(TCV | M14R \cap M14L \cap O13C) \times P(M14R \cap M14L \cap O13C) \\ &= \mathrm{P}(\mathrm{TCV} | M14R \cap M14L \cap O13C) \times P(O13C | M14R \cap M14L) \times P(M14R \cap M14L) \\ &= \mathrm{P}(\mathrm{TCV} | M14R \cap M14L \cap O13C) \times P(O13C | M14R \cap M14L) \times P(M14R | M14L) \times P(M14L) \end{aligned} \quad (2)$$

The symbol "∩" stands for "and." The symbol "|" stands for "given."

The first factor in equation 2:

$$\mathrm{P}(\mathrm{TCV}|M14R \cap M14L \cap O13C)$$

is the probability of a TCV given that a missed approach from ORD runway 14R, a missed approach from ORD runway 14L and an overshoot to MDW runway 13C have all occurred. This is the probability that is estimated from the simulation of scenario 1. The application of equation 1 to the curve fitted to the CPA data determines that

$$\mathrm{P}(\mathrm{TCV}|M14R \cap M14L \cap O13C) = 3.8 \times 10^{-5}$$

The second factor in equation 2:

$$P(O13C|M14R \cap M14L)$$

is the probability that an overshoot to MDW runway 13C occurs given that missed approaches occur on both ORD runways 14R and 14L. Since the occurrence of an overshoot to MDW runway 13C is independent of the missed approaches from ORD runways 14R and 14L, this probability can be written as:

$$P(O13C|M14R \cap M14L) = P(O13C)$$

Recent radar data indicates that 2 overshoots occurred out of 221 vectored turns to final to MDW runway 13C. Thus, 2/221 is an estimate of the overshoot probability. If we assume the probability of an overshoot remains constant over time and that one overshoot incident is independent of any other, then overshoots can be modeled as Bernoulli events.

In a Bernoulli experiment, two possible events can occur. The two events are usually called "success" and "failure." In this case, the two events are "overshoot" and "non-overshoot." When a Bernoulli experiment is repeated a number of times, N and S successes are observed, then S/N is an estimate of the actual probability P of a success. The number of successes S will vary with different samples of size N leading to different estimates of N. Therefore, a confidence interval is computed to determine the possible range of the actual probability P. The 99% confidence interval for P given the observed rate 2/221 is $4.7 \times 10^{-4} \leq P \leq 4.1 \times 10^{-2}$. Therefore, this is only a one percent chance that the actual rate is more than 4.1×10^{-2}. This value will be used for the estimate of $P(O13C)$.

The third factor in equation 2:

$$P(M14R|M14L)$$

is the probability of a missed approach from ORD runway 14R, given that a missed approach from ORD runway 14L occurs. These events may not be independent, because weather conditions that force a missed approach may also tend to cause a missed approach from the other.

The probability of a single missed approach is internationally estimated to be 1×10^{-2}. If the two events are independent, then the probability of a missed approach from ORD runway 14R, given a missed approach from ORD runway 14L occurred, would also be 1×10^{-2}. If the two events are dependent, then the conditional probability could be as high as 1×10^{-1}. Therefore, the value of $P(M14R|M14L)$ will be assumed to be 1×10^{-1}.

The fourth factor in equation 2:

$$P(M14L)$$

is the probability of a missed approach from ORD runway 14L. This probability is internationally assumed to be 1×10^{-2}.

The risk associated with scenario 1 can now be computed from equation 2 as:

$$P(TCV) = 3.8 \times 10^{-5} \times 4.1 \times 10^{-2} \times 1 \times 10^{-1} \times 1 \times 10^{-2} = 1.6 \times 10^{-9}$$

3.4. Analysis of Risk Associated with Scenario 2

Scenario 2 is similar to scenario 1. The difference is that a fourth event, one engine inoperative, must also occur. Therefore, four events have to occur: a missed approach from ORD runway 14R, a missed approach from ORD runway 14L, an overshoot of the turn to final to MDW runway 14R, and the failure of one engine in the missed approach aircraft from ORD runway 14R. In scenario 2, the missed approach from ORD runway 14R is unable to turn because of the missed approach from ORD runway 14L.

Suppose that the event "missed approach from ORD runway 14R" is denoted M14R, the event "missed approach from ORD runway 14L" is denoted by M14L, the event "overshoot the approach to MDW runway 13C" is denoted by O13C, and the event "failed engine" is denoted by FE, then the probability of a TCV caused by the conditions related to scenario 2 is given by the following probability equation.

$$\begin{aligned} P(TCV) &= P(TCV \cap M14R \cap M14L \cap O13C \cap FE) \\ &= P(TCV|M14R \cap M14L \cap O13C \cap FE) \times P(O13C|M14R \cap M14L \cap FE) \quad (3) \\ &\quad \times P(FE|M14R \cap M14L) \times P(M14L|M14R) \times P(M14R) \end{aligned}$$

The first factor in equation 3:

$$\mathrm{P(TCV}|M14R \cap M14L \cap O13C \cap FE)$$

is the probability of a TCV given that a missed approach from ORD runway 14R, a missed approach from ORD runway 14L, an overshoot to MDW runway 13C, and a failed engine in the missed approach aircraft from ORD runway 14R have all occurred.

This is the probability that is estimated from the simulation of scenario 2. The application of equation 1 to the curve fitted to the CPA data determines that

$$\mathrm{P}(\mathrm{TCV} | M14R \cap M14L \cap O13C \cap FE) = 6.3 \times 10^{-4}.$$

The second factor in equation 3:

$$P(O13C | M14R \cap M14L \cap FE)$$

is the probability that an overshoot to MDW runway 13C occurs, given that missed approaches occur on both ORD runways 14R and 14L, and a failed engine occurs on the missed approach aircraft from ORD runway 14R. Since the occurrence of an overshoot to MDW runway 13C is independent of the missed approaches from ORD runways 14R and 14L, and a failed engine occurs on the missed approach aircraft from ORD runway 14R, this probability can be written as:

$$P(O13C | M14R \cap M14L \cap FE) = P(O13C).$$

This probability is the same as the second factor of equation 2 for scenario 1. Therefore:

$$P(O13C | M14R \cap M14L \cap FE) = P(O13C) = 4.1 \times 10^{-2}.$$

The third factor in equation 3:

$$P(FE | M14R \cap M14L)$$

is the probability of a failed engine on the missed approach aircraft from ORD runway 14R given that a missed approach from ORD runways 14R and 14L have occurred. Since the probability of a failed engine is independent of the occurrence of missed approaches from ORD runways 14R and 14L, the third factor becomes:

$$P(FE | M14R \cap M14L) = P(FE).$$

Historical data indicates that the probability of a failed engine is on the order of 1×10^{-5}.

Therefore,

$$P(FE | M14R \cap M14L) = P(FE) = 1 \times 10^{-5}.$$

The fourth and fifth factors of equation 3,

$$P(M14L | M14R) \text{ and } P(M14R)$$

have the same values as in scenario 1.

Therefore,

$$P(M14L|M14R) = 1\times10^{-1}$$

and

$$P(M14R) = 1\times10^{-2}.$$

The risk associated with scenario 2 can now be computed from equation 3 as:

$$P(TCV) = 6.3\times10^{-5}\times4.1\times10^{-2}\times1\times10^{-5}\times1\times10^{-1}\times1\times10^{-2} = 2.6\times10^{-14}$$

3.5. Analysis of Risk Associated with Scenario 3

Scenario 3 is similar to scenario 1. The difference is that a missed approach from ORD runway 14L does not occur and the missed approach from ORD 14R can be turned away from the ILS approach to MDW runway 13C. Therefore, three events have to occur; a missed approach from ORD runway 14R, a landing on ORD runway 14L, and an overshoot of the turn to final to MDW runway 14R.

As in scenarios 1 and 2, the event "missed approach from ORD runway 14R" is denoted M14R, the event "missed approach from ORD runway 14L" is denoted by M14L, and the event "overshoot the approach to MDW runway 13C" is denoted by O13C. The event "aircraft approaching ORD runway 14L lands and does not perform a missed approach," is the negative of M14L and is denoted by $\overline{\text{M14L}}$. The probability of a TCV caused by the conditions related to scenario 3 is given by the following probability equation.

$$\begin{aligned} P(TCV) &= P(TCV\cap M14R\cap\overline{M14L}\cap O13C) \\ &= P(TCV|M14R\cap\overline{M14L}\cap O13C)\times P(O13C|M14R\cap\overline{M14L}) \qquad (4) \\ &\quad\times P(\overline{M14L}|M14R)\times P(M14R) \end{aligned}$$

The first factor in equation 4:

$$\text{P}(\text{TCV}|M14R\cap\overline{M14L}\cap O13C)$$

is the probability of a TCV given that a missed approach from ORD runway 14R, a landing on ORD runway 14L, and an overshoot to MDW runway 13C have all occurred. This is the probability that is estimated from the simulation of scenario 3. The application of equation 1 to the curve fitted to the CPA data determines that

$$\text{P}(\text{TCV}|M14R\cap\overline{M14L}\cap O13C) = 5.6\times10^{-5}.$$

The second factor in equation 4:

$$P(O13C \mid M14R \cap \overline{M14L})$$

is the probability that an overshoot to MDW runway 13C occurs given that missed approach occurs on ORD runway 14R and a landing on ORD runway 14L. Since the occurrence of an overshoot to MDW runway 13C is independent of the missed approach from ORD runway 14R and the landing on ORD runway 14L, this probability can be written as:

$$P(O13C \mid M14R \cap \overline{M14L}) = P(O13C).$$

This probability is the same as the second factor of equation 2 for scenario 1. Therefore:

$$P(O13C \mid M14R \cap \overline{M14L}) = P(O13C) = 4.1 \times 10^{-2}$$

The third factor in equation 4 is the probability that a missed approach from ORD 14L does not occur, given that a missed approach from ORD 14R does occur. This probability can be found from the probability that a missed approach from ORD 14L occurs, given that missed approach from ORD 14R does occur. The value of the third factor is given by:

$$P(\overline{M14L} \mid M14R) = 1 - P(M14L \mid M14R) = 9 \times 10^{-1}$$

The fourth factor of equation 4,

$$P(M14R)$$

has the same value as in scenario 1. Therefore,

$$P(M14R) = 1 \times 10^{-2}.$$

The risk associated with scenario 3 can now be computed from equation 3 as:

$$P(TCV) = 5.6 \times 10^{-5} \times 4.1 \times 10^{-2} \times 9 \times 10^{-1} \times 1 \times 10^{-2} = 2.1 \times 10^{-8}$$

3.6. Analysis of Risk Associated with Scenario 4

Scenario 4 is similar to scenario 2. The difference is that a landing occurs on ORD runway 14L. Therefore, four events have to occur; a missed approach from ORD runway 14R, a landing on ORD runway 14L, an overshoot of the turn to final to MDW runway 14R, and the failure of one engine in the missed approach aircraft from ORD runway 14R.

As in scenarios 1, 2, and 3, the event "missed approach from ORD runway 14R" is denoted M14R, the event "missed approach from ORD runway 14L" is denoted by M14L, the event "overshoot the approach to MDW runway 13C" is denoted by O13C, and the event "failed engine" is denoted by FE. The event "aircraft approaching ORD runway 14L lands and does not perform a missed approach," is the negative of M14L and is denoted by $\overline{\mathrm{M14L}}$. The probability of a TCV caused by the conditions related to scenario 4 is given by the following probability equation.

$$
\begin{aligned}
P(TCV) &= P(TCV \cap M14R \cap \overline{M14L} \cap O13C \cap FE) \\
&= P(TCV | M14R \cap \overline{M14L} \cap O13C \cap FE) \times P(O13C | M14R \cap \overline{M14L} \cap FE) \\
&\quad \times P(FE | M14R \cap \overline{M14L}) \times P(\overline{M14L} | M14R) \times P(M14R)
\end{aligned} \quad (5)
$$

The first factor in equation 5:

$$\mathrm{P(TCV} | M14R \cap \overline{M14L} \cap O13C \cap FE)$$

is the probability of a TCV given that a missed approach from ORD runway 14R, a landing on ORD runway 14L, an overshoot to MDW runway 13C, and a failed engine in the missed approach aircraft from ORD runway 14R have all occurred. This is the probability that is estimated from the simulation of scenario 4. The application of equation 1 to the curve fitted to the CPA data determines that

$$\mathrm{P(TCV} | M14R \cap \overline{M14L} \cap O13C \cap FE) = 6.5 \times 10^{-4} .$$

The second factor in equation 5:

$$P(O13C | M14R \cap \overline{M14L} \cap FE)$$

is the probability that an overshoot to MDW runway 13C occurs given that a missed approach occurs from ORD runway 14R, a landing occurs on ORD runway 14L, and a failed engine occurs on the missed approach aircraft from ORD runway 14R. Since the occurrence of an overshoot to MDW runway 13C is independent of the missed approach from ORD runway 14R, the landing on ORD runway 14L, and a failed engine occurrence on the missed approach aircraft from ORD runway 14R, this probability can be written as:

$$P(O13C | M14R \cap \overline{M14L} \cap FE) = P(O13C).$$

This probability is the same as the second factor of equation 2 for scenario 1. Therefore:

$$P(O13C | M14R \cap M14L \cap FE) = P(O13C) = 4.1 \times 10^{-2}.$$

The third factor in equation 5:

$$P(FE \mid M14R \cap \overline{M14L})$$

is the probability of a failed engine on the missed approach aircraft from ORD runway 14R given that a missed approach from ORD runway 14R and a landing on ORD runway 14L have occurred. Since the probability of a failed engine is independent of the occurrence of a missed approach from ORD runway 14R and a landing on ORD 14L, the third factor becomes:

$$P(FE \mid M14R \cap \overline{M14L}) = P(FE).$$

Historical data indicates that the probability of a failed engine is on the order of 1×10^{-5}. Therefore,

$$P(FE \mid M14R \cap \overline{M14L}) = P(FE) = 1 \times 10^{-5}.$$

The fourth and fifth factors of equation 5,

$$P(\overline{M14L} \mid M14R) \text{ and } P(M14R)$$

have the same values as in scenario 1 and 3. Therefore,

$$P(\overline{M14L} \mid M14R) = 9 \times 10^{-1}$$

and

$$P(M14R) = 1 \times 10^{-2}.$$

The risk associated with scenario 4 can now be computed from equation 5 as:

$$P(TCV) = 6.5 \times 10^{-4} \times 4.1 \times 10^{-2} \times 1 \times 10^{-5} \times 1 \times 10^{-1} \times 1 \times 10^{-2} = 2.7 \times 10^{-13}$$

3.7. Analysis of Total Risk

Paragraphs 3.3, 3.4, 3.5, and 3.6 presented the risk associated with each of the four scenarios. However, during approach operations to ORD runways 14L, 14R, and MDW runway 13C, a TCV could be caused by the occurrence of any one of the four scenarios. If we denote the occurrence of a TCV during scenario 1 by SC1, during scenario 2 by SC2, during scenario 3 by SC3, and during scenario 4 by SC4, then the probability of a TCV can be written as follows:

$$P(TCV) = P(SC1 \cup SC2 \cup SC3 \cup SC4) \qquad (6)$$

where the symbol "$\cup$" stands for the word "or."

The four scenarios are mutually exclusive events, i.e., they cannot occur simultaneously. This means that equation 6 can written as follows:

$$P(TCV) = P(SC1 \cup SC2 \cup SC3 \cup SC4) = P(SC1) + P(SC2) + P(SC3) + P(SC4)$$

Thus, the total probability or risk associated with approach operations to ORD runways 14R, 14L, and MDW 13C, can be determined as follows:

$$P(TCV) = 1.6 \times 10^{-9} + 2.6 \times 10^{-14} + 2.1 \times 10^{-8} + 2.7 \times 10^{-13} = 2.3 \times 10^{-8}$$

The probability or risk associated with approach operations to ORD runways 14R, 14L, and MDW 13C, is less than the target level of safety.

4.0. Results and Conclusions

4.1. Given the assumptions and constraints of the ASAT simulation, this evaluation shows that the level of safety for conducting independent approach operations at ORD to runways 14L and 14R, while MDW is conducting approach operations to 13C is less than the target level of safety.

4.2. While the results reported in paragraph 4.1 support the case for independent, i.e. non-staggered operations at ORD runways 14L and 14R, the issue of radar separation criteria is not addressed by this study. Factors such as a waiver to Air Traffic procedures, the additional safety benefit of a dedicated controller to monitor missed approaches at ORD and the subsequent impact on MDW 13C traffic, and the equipment suite, including surveillance and communication, available to the "monitor" controller should be considered for operational implementation.

5.0. List of References

1. FAA Order 7110.65, Air Traffic Control.

2. Contract DTFA02-02-F-15359, Deliverable 1 Definition of Scenarios.

3. Contract DTFA02-02-F-15359, Deliverable 2 Radar Tracks Data Analysis.

4. Contract DTFA02-02-F-15359, Deliverable 3 Air Traffic Controller Human Factors Related Data Analysis.

5. Contract DTFA02-02-F-15359, Deliverable 4 ATC Model and ASAT Customization (combined with Deliverable 1).

6. Contract DTFA02-02-F-15359, Deliverable 5 ASAT Runs.

7. Contract DTFA02-02-F-15359, Deliverable 6 Statistical Analysis.

8. Contract DTFA02-02-F-15359, Deliverable 7 Technical Report (combined with Deliverable 6).

9. DOT Technical Report DOT/FAA/RD-91/5, Precision Runway Monitor Demonstration Report, February 1991.