Determination of In-trail Distance at Various Ranges from Runway Threshold at Chicago O'Hare International Airport (ORD) Using Radar Tracks Data

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Determination of In-trail Distance at Various Ranges from Runway Threshold at Chicago O'Hare International Airport (ORD) Using Radar Tracks Data

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The purpose of this study was to determine if the current separation standard under which consecutive aircraft approaching a single runway maintain a minimum in-trail distance of 2.5 NM while established on the last 10 NM of final approach, can be extended to 20 NM from the runway threshold. This study concluded that the variations in in-trail separation at ranges from 0 to 10 NM and 10 NM to 20 NM are similar. Based on this conclusion it is reasonable to expect that 2.5 NM in-trail spacing on final approach could be supported 10 to 20 NM from the runway threshold with safety levels equivalent to those achieved 0 to 10 NM from the threshold within the restrictions of the current separation standards.
Executive Summary

Current Air Traffic Control (ATC) radar separation standards are contained in FAA Order 7110.65, Air Traffic Control. When within 40 NM of the radar system antenna and in single sensor mode, these standards require controllers to maintain a minimum of 3.0 NM spacing between in-trail aircraft pairs. When the requirements of FAA order 7110.65, paragraph 5-5-4.g., are met, such as the aircraft are established on final approach course and within 10 NM of the landing runway, the minimum required in-trail separation can be reduced to 2.5 NM.

A previous study has concluded that decreased in-trail separation during the final approach phase of the flight meets the FAA’s established target level of safety for such operations in respect to the risk of a mid-air collision.

The purpose of this study was to determine if the current rule allowing a minimum in-trail distance of 2.5 NM within 10 NM from the runway threshold could be extended to 20 NM without significant reduction in safety. The study was based on analysis of radar tracks of traffic approaching runways 14R and 22R at Chicago O’Hare International Airport (ORD). These tracks were collected by the C90 Automated Radar Terminal System (ARTS) for the period of July 1998 to April 1999. The radar tracks were subsequently analyzed in order to determine the variations in in-trail separation between consecutive aircraft at various distances from the approaching threshold. The purpose of the analysis was to determine whether variations in in-trail separation vary with distance from runway threshold. The study was conducted by the FAA, Flight Operations Simulation and Analysis Branch (AFS-440) and Air Traffic Simulation, Inc. (ATSI).

This study concluded that the variations in in-trail separation at ranges from 0 to 10 NM and 10 NM to 20 NM are similar. Since at times, as the data show, aircraft might operate at in-trail distances of between 5 NM and 6 NM when at ranges of between 10 NM and 20 NM from the runway landing threshold, some operational benefits might be obtained by reducing the minimum required in-trail separation at those ranges from 3.0 NM to 2.5 NM. This change is not expected to adversely affect the safety of the operation.

The following conclusions were drawn based on the analysis:

- The actual value of in-trail distance varies along the approach phase of the flight and decreases as distance from runway threshold decreases. This is known as the compression effect.
- The actual variation in in-trail distances along the approach to land can be considered constant.
- Separation standards are being consistently maintained at the various distances from runway threshold evaluated in this study.
Based on the statistical analysis of the separation data and other considerations, it is reasonable to expect that the minimum 2.5 NM in-trail spacing on final approach could be supported 10 to 20 NM from the runway threshold, with safety levels equivalent to those achieved within 10 NM of the landing runway when the restrictions of the current standard are applied.
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1.0. Introduction

Current Air Traffic Control (ATC) radar separation standards are contained in FAA Order 7110.65, Air Traffic Control (Reference 1). When within 40 NM of the radar system antenna and in single sensor mode, these standards require controllers to maintain a minimum of 3.0 NM spacing between in-trail aircraft pairs. When the requirements of Reference 1, paragraph 5-5-4.g., are met, such as the aircraft are established on final approach course and within 10 NM of the landing runway, the minimum required in-trail separation can be reduced to 2.5 NM.

A previous study (Reference 2) has concluded that decreased in-trail separation during the final approach phase of the flight meets the FAA's established target level of safety for such operations in respect to the risk of a mid-air collision.

The purpose of this study was to determine if the current rule allowing a minimum in-trail distance of 2.5 NM within 10 NM from the runway threshold could be extended to 20 NM without significant reduction in safety. The study was based upon analysis of radar tracks of traffic approaching runways 14R and 22R at Chicago O'Hare International Airport (ORD). These tracks were collected by the C90 Automated Radar Terminal System (ARTS) for the period of July 1998 to April 1999. The radar tracks were subsequently analyzed in order to determine the variations in in-trail separation between consecutive aircraft at various distances from the approaching threshold. The purpose of the analysis was to determine whether variations in in-trail separation vary with distance from runway threshold. The study was conducted by the FAA, Flight Operations Simulation and Analysis Branch (AFS-440) and Air Traffic Simulation, Inc. (ATSI).

This study concluded that the variations in in-trail separation at ranges from 0 to 10 NM and 10 NM to 20 NM are similar. Since at times, as the data show, aircraft might operate at in-trail distances of between 5 NM and 6 NM when at ranges of between 10 NM and 20 NM from the runway landing threshold, some operational benefits might be obtained by reducing the minimum required in-trail separation at those ranges from 3.0 NM to 2.5 NM. This change is not expected to adversely affect the safety of the operation.

2.0. Description of the Model

The model developed to support this study was based solely on the analysis of a large number (6,874) of radar tracks of aircraft approaching and landing on runways 14R and 22R at ORD. Figure 1 shows the various steps in model development and execution.

ATSI developed a fast-time, multi-function computer program for radar tracks display and analysis, called InTrailTracks™. The program can display and statistically analyze in-trail distances between consecutive aircraft approaching to a single runway using a large set of radar tracks.
The program was used to generate two databases as follows:

a. One database contains data generated by the program using information from radar tracks when both aircraft being tracked were within a range of 0 NM to 10 NM from the landing runway threshold.

b. The other database contains data generated using information from radar tracks when both aircraft being tracked were within a range of 10 NM to 20 NM from the landing threshold.

The two databases contained radar track data for aircraft approaching runways 14R and 22R. Each of the databases was analyzed to determine their individual statistical characteristics. The statistical characteristics of the two databases were compared in order to determine the variation in in-trail distance between the two data sets, i.e., 0 NM to 10 NM and 10 NM and 20 NM. Lastly, based upon the study results, conclusions were drawn.

Figure 2 shows a typical InTrailTracks™ screen capture depicting traffic approaching to runways 14R and 22R at ORD. Figure 2 depicts the boundaries of the areas of interest, i.e., the blue areas are from 20 NM to 10 NM from the respective runway landing threshold, and the red areas are from 10 NM to 0 NM from the respective runway landing threshold.
Figure 1: Model Development and Execution
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Figure 2: InTrailTracks™ Screen Capture of ORD Runways 14R and 22R Arriving Traffic

3.0. Summary of Data Analysis

Note: For the purpose of this study, the tool measured in-trail distances between two consecutive aircraft at ranges of 0 to 10 NM from the runway threshold and 10 to 20 NM from runway threshold. Since a significant number of aircraft are vectored to join the final approach at various distances from runway threshold, the number of data points at closer ranges to the threshold is greater than the number of data points at greater distances from the runway. Data from both runways 22R and 14R were analyzed.

Figure 3 shows a histogram of in-trail distances for aircraft operations from 0 NM to 10 NM from landing runway threshold. This data contains both runways 14R and 22R landing aircraft.
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Figure 4 shows a histogram of in-trail distances for aircraft operations from 10 NM to 20 NM from landing runway threshold. Again, the data contains both runways 14R and 22R landing aircraft.

For both cases, the data was analyzed to determine the Probability Density Function (PDF) that best fits the data. If the PDF can be described by a function that is bounded at the lower end, this will indicate that in-trail distances are extremely unlikely to be smaller than the lower value of the bounded function.

3.1. Statistical Analysis of Data from 0 NM to 10 NM

This dataset fits a Johnson SB distribution with the following parameters:

\[
\begin{align*}
\text{min} & = 2.31327 \\
\lambda & = 8.47799 \\
\gamma & = 0.955157 \\
\delta & = 1.06009
\end{align*}
\]

The Johnson family of empirical distributions is based on transformations of a standard normal variate. Appendix A provides a discussion of their properties and determination.
Figure 5: 0 NM to 10 NM Data Johnson Distribution

Figure 5 shows a histogram of the 0 NM to 10 NM data overlain by the best-fit Johnson distribution. As Figure 5 shows, the Johnson SB distribution is bounded on the low end by 2.31327 indicating that if the fit truly represented the distribution, no in-trail values lower than 2.3 NM would occur.

The probability density function for this distribution is given by:

\[
f(x) = \begin{cases} 
\frac{\delta}{\sqrt{2\pi} y(1-y)\lambda} \exp\left(-\frac{1}{2} \left(y + \delta \ln\left(\frac{y}{1-y}\right)\right)^2\right) & \text{if } x > \min \\
0 & \text{if } x \leq \min 
\end{cases}
\]

where \( y = \frac{x - \min}{\lambda} \)

Using this distribution, the probability of occurrence of an in-trail distance of less than 2.5 NM can be calculated as:

\[
P(X < 2.5) = \int_{-\infty}^{2.5} f(x)dx = 0.00108444
\]
or just over a tenth of one per cent.

3.2. Statistical Analysis of Data from 10 NM to 20 NM

This dataset fits a Johnson SB distribution with the following parameters:

\[ \begin{align*}
\text{min} &= 2.83759 \\
\lambda &= 7.32723 \\
\gamma &= 0.399323 \\
\delta &= 0.966228 
\end{align*} \]

Figure 6 shows a histogram of the 10 NM to 20 NM data overlain by the best-fit Johnson distribution. As Figure 6 shows, the Johnson SB distribution is bounded on the low end by 2.83759 indicating that if the fit truly represented the distribution, no in-trail distance values lower than 2.8 NM would occur.

As above, the probability density function is given by:

\[ \text{Fitted Density} \]
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\[
f(x) = \begin{cases} \frac{\delta}{\sqrt{2\pi}y(1-y)\lambda} \exp\left(-\frac{1}{2} y + \delta \ln\left(\frac{y}{1-y}\right)\right) & \text{if } x > \text{min} \\ 0 & \text{if } x \leq \text{min} \end{cases}
\]

where \( y = \frac{x - \text{min}}{\lambda} \)

Using this distribution, the probability of occurrence of an in-trail distance value of less than 3.0 NM can be calculated as:

\[
P(X < 3.0) = \int_{-\infty}^{3.0} f(x)dx = 0.000557843
\]

or just over a 20th of one percent.

3.3. Surveillance System Considerations

A factor that must be considered in the evaluation of the comparative safety of the 0-10 NM operation versus the 10-20 NM operation, is the ability of the surveillance system to support separation standards. According to Reference 1 requirements, the current 0-10 NM operation must be carried out within 40 NM of the radar antenna. The normal configuration for airports using the reduced 2.5 NM separation is for the radar to be located on the airport. This results in the primary error component of interest being range error rather than azimuth error. On current generation terminal radars, there is no range dependent error in the normal operating volume, i.e., the expected range error at 20 NM would be the same as at 5 NM. For radar configurations where the antenna is not located at the landing airport, but the 10-20 NM operation at that airport would still be within 40 NM of the radar antenna, the differences in azimuth error due to range will not adversely impact the application of 2.5 NM separation between aircraft established on final approach within 20 NM of the runway.

4.0. Results and Conclusions

The following conclusions can be drawn based on the analysis of the radar tracks data for aircraft approaching runways 14R and 22R at Chicago O'Hare International Airport:

- The actual value of in-trail distance varies along the approach phase of the flight and decreases as distance from runway threshold decreases. This is known as the compression effect.
- The actual variation in in-trail distances along the approach to land can be considered constant.
• Separation standards are being consistently maintained at the various distances from runway threshold evaluated in this study.

• Based on the statistical analysis of the separation data and other considerations, it is reasonable to expect that the minimum 2.5 NM in-trail spacing on final approach could be supported 10 to 20 NM from the runway threshold, with safety levels equivalent to those achieved within 10 NM of the landing runway when the restrictions of the current standard are applied.

5.0. References


Appendix A

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:

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

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 $\varepsilon$ and is unbounded on the right. By performing a certain transformation of the parameters $\delta$ and $\gamma$, the curves can be converted to the log-normal distribution.

2. The $S_B$ family is characterized by the transformation:

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

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 $\varepsilon$ and on the right by $\varepsilon + \lambda$. These curves resemble the Weibul or extreme-value families. The parameters $\gamma$ and $\delta$ are shape parameters, $\varepsilon$ is a location parameter, and $\lambda$ is a scale parameter.

3. The $S_U$ family is characterized by the transformation:

$$z = \gamma + \delta \sinh^{-1} \left( \frac{x - \varepsilon}{\lambda} \right), \quad -\infty < x < \infty.$$
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 \( \gamma \) and \( \delta \) are shape parameters, \( \varepsilon \) is a location parameter, and \( \lambda \) is a scale parameter.

In order to use the Johnson family of curves it is necessary to invert equations 1, 2, and 3, i.e., each of the equations must be solved for \( x \).

1. The \( S_L \) transformation after inversion is:

\[
x = \varepsilon + \lambda \exp\left(\frac{z - \gamma}{\delta}\right), \quad -\infty < z < \infty. \tag{4}
\]

2. The \( S_B \) transformation after inversion is:

\[
x = \varepsilon - \frac{\lambda}{1 - \exp\left(\frac{\gamma - z}{\delta}\right)}, \quad -\infty < z < \infty. \tag{5}
\]

3. The \( S_U \) transformation after inversion is:

\[
x = \varepsilon + \lambda \sinh\left(\frac{z - \gamma}{\delta}\right), \quad -\infty < z < \infty. \tag{6}
\]

Since 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:

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

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

2. The probability density function of a member of the Johnson \( S_B \) family has the following form:
3. The probability density function of a member of the Johnson Su family has the following form:

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

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

**Sampling from a Johnson Curve.**

After the appropriate Johnson curve has been selected and the parameters \(\gamma, \delta, \varepsilon, \) and \(\lambda\) have been determined, 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 (4) to obtain the random variate \(x\). If the Johnson curve is of type \(S_B\) then substitute \(z\) into equation (5) to obtain the random variate \(x\). If the Johnson curve is of type \(S_L\) then substitute \(z\) into equation (6) to obtain the random variate \(x\).