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Potential Benefits of Terminal Airspace Traffic Automation for Arrivals

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Advanced air traffic management systems such as the Center/TRACON Automation System should yield a wide range of benefits, including increased airport arrival capacity and reduced aircraft delays. To estimate the traffic flow benefits achievable from future terminal airspace automation, live radar information was used to perform an analysis of current aircraft landing rates and separations at the Dallas/Fort Worth International Airport. Separation statistics that result when controllers balance complex procedural constraints against the need to maintain high landing rates are presented. In addition, the analysis estimates the potential for airport capacity improvements by determining the unused landing opportunities that occur during rush traffic periods. Results suggest a large potential for balancing runway loads and improving the accuracy and consistency of spacing between arrivals on final approach, leading to a potential increase in arrival capacity of at least 15% for the Dallas/Fort Worth International Airport and similar airports. This capacity increase may lower operating costs for airport users and substantially reduce the need for future airport expansions.

Introduction

ADVANCED air traffic management systems such as the Center/TRACON Automation System (CTAS)[1] should yield a wide range of benefits, including increased airport arrival capacity and reduced aircraft delays. To estimate the traffic flow benefits achievable from future terminal airspace automation, an analysis of aircraft landing rates and separations was performed for the Dallas/Fort Worth International Airport (DFW) using live radar information. The primary goal was to obtain a reference baseline for the assessment of CTAS as it is tested at the airport; a secondary goal was to aid in the further development of CTAS through an increased understanding of controller and pilot practices during the final approach segment of flight.

The longitudinal separation characteristics of arrival traffic flow on final approach at DFW were identified based on radar track data, recorded for a selected set of arrival rushes over a period from October 1994 to April 1995. Although the data set is not comprehensive, the analysis results are useful for obtaining an approximation of savings achievable by optimizing traffic flow in terminal airspace. Observed trends in the utilization of runways and controller practices in spacing aircraft are also useful for the design of a terminal airspace automation tool and the tuning of its internal parameters. This paper presents an overview of the study, including highlights of the results. A more detailed description of the data gathering and analysis procedures, a comprehensive presentation of results, and recommendations for continued study may be found in Ref. 2.

Dallas/Fort Worth International Airport

Figure 1 is a plan view of the runways and final approach area at DFW. Two sets of parallel runways accept arrivals from north and south (35 R/L and 36 R/L or 17 R/L and 18 R/L), and two diagonal runways accept arrivals from the northwest and southeast (31 R/L and 13 R/L). During north flow, some or all of Runways 31, 35, and 36 are active, and during south flow, some or all of Runways 13, 17, and 18 are active. The gate area is located between the two sets of north/south runways. The airport elevation is approximately 600 ft above mean sea level (MSL).

The outer marker and final approach fix (FAF) locations, approximately 5 n miles from the runway thresholds, are coincident at DFW. The glide slope intercept altitude for each FAF except for Runway 31R is 2300 ft MSL; for Runway 31R it is 2400 ft MSL. All approaches follow direct line-of-sight paths from the FAF to the threshold, except for a special noise-abatement approach that is often used for Runway 31R during visual conditions. For that approach, referred to as the stadium visual approach, aircraft are directed over Texas Stadium and are then required to make a left turn to acquire the runway approximately 2 n miles from the threshold.

Separation Regulations

During the approach and landing phases of flight, the Federal Aviation Administration (FAA) mandates that an aircraft following another aircraft must be longitudinally separated by a specified minimum distance to mitigate the danger of wake turbulence caused by the leading aircraft. Aircraft are classified by the FAA as small, large, or heavy based on their maximum certified takeoff weights as follows: small $\leq$ 12,500 lb; 12,500 lb $<$ large $\leq$ 300,000 lb; and heavy $>$ 300,000 lb. The Boeing 757 (B757), though classified as large, has been given a special set of separation criteria because increased wake turbulence has been attributed to this type of aircraft.[3]

Table 1 shows the FAA approach and landing separation minima for each combination of lead/trail aircraft weight classifications and the B757. Controller clearances must comply with the separation minima up to the time that the lead aircraft crosses the runway threshold. Under dry runway conditions, DFW utilizes reduced separation criteria, as specified in Ref. 3: the 3–n mile aircraft separation minima are reduced to 2.5 n miles.

Although captains assume ultimate responsibility for the safety of their aircraft, the air traffic controllers are responsible for maintaining separation between aircraft operating on instrument flight rules flight plans (such as commercial air carriers). However, pilots can accept responsibility for separation between their aircraft and another aircraft that they can see. In this situation, the pilots are responsible for maintaining the amount of separation that they deem safe. The transfer of responsibility requires direct communication between the controllers and the pilots.

Pilots are often requested to accept responsibility for visual separation under visual meteorological conditions (VMC), which

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typically corresponds to a ceiling greater than or equal to 500 ft above the minimum vectoring altitude and visibility greater than or equal to 3 statute miles (Ref. 3). The minimum vectoring altitude at DFW varies between 2000 and 2200 ft MSL. Therefore, at DFW, the minimum ceiling for VMC is approximately 2000 ft above ground level (AGL).

Lower ceilings or visibility correspond to instrument meteorological conditions (IMC). Under IMC, pilots conduct instrument approaches using either a precision or a nonprecision procedure; precision approaches use equipment to provide vertical and lateral course guidance, whereas nonprecision approaches provide only lateral guidance. Under these conditions, the air traffic controllers are responsible for providing clearances to the pilots to maintain separation with the leading aircraft, although the pilots may accept responsibility if they have visual contact.

A more detailed description of FAA separation regulations for radar arrivals may be obtained from the FAA air traffic control handbook.[3]

Assumptions

Aircraft arrive at the runways in streams from several terminal radar approach control (TRACON) feeder gates; each of these streams may in turn be separated into two or more independent streams based on aircraft type. All streams must merge to land on three or fewer runways at DFW. Previous findings based on simulation have indicated that the final approach segment is the critical point of constriction for arriving aircraft if the terminal airspace is managed effectively.

The analysis assumed that if the number of aircraft arriving into the terminal airspace equals or exceeds the airport capacity, unusable time gaps between aircraft on landing can be eliminated through effective management of aircraft in the terminal airspace. In estimating delays that could be reduced by terminal area automation, the analysis also assumed that the specified airport acceptance rates accurately reflected the abilities of TRACON controllers to handle aircraft in the terminal airspace.

Table 1 Minimum required in-trail landing separations (leading aircraft down, trailing aircraft across)

Minimum required separation, n miles	Heavy	Large	Small	B757
Heavy	4	5	6	5
Large	3	3	4	3
Small	3	3	3	3
B757	4	4	5	4

Data Recording and Reduction

Radar track data were supplied using a direct feed from the Fort Worth Air Route Traffic Control Center (hereafter called the Center) radar and the DFW ASR-9 terminal radar. Center and terminal radar recordings were made simultaneously to identify arrival rush periods based on delay buildup in the Center and to provide Center delays of each aircraft to augment the analysis. The combined recordings, which started up to 30 min before crossing the feeder gate and continued until the TRACON radar track dropped out near the runway threshold, provided position histories of each arriving aircraft.

The rush-period data set consisted of 30 individual rush periods, with each period containing landings to all active runways. At least two runways were active for all recordings. The following information was gathered to support the analysis: 1) flight rules in effect, 2) airport visibility, 3) airport ceiling, 4) runway conditions, 5) wind speed and direction at the airport, 6) approach type in effect (simultaneous or staggered), 7) the aircraft acceptance rate, and 8) special conditions or restrictions in effect.

Rush periods were identified as large contiguous periods for which landing demand was observed to exceed the DFW aircraft acceptance rate. They corresponded to a buildup of delay for arrivals while they were still in en route airspace. The Center delays incurred by each aircraft were estimated by using the Center recordings as input to CTAS, which computed estimated times of arrival (ETA) at the TRACON feeder gates. The point at which an aircraft was predicted to cross the feeder gate 19 min in the future was used as the measuring point in the Center. In computing the ETA values, CTAS assumes that undelayed direct routing is used between this measuring point and the feeder gate. The ETA was subtracted from the actual feeder gate crossing time to obtain the delay estimate.

The rush periods were classified as VMC or IMC, based on weather conditions at the airport. To ensure that any observed arrival gaps were not caused by the need to allow other aircraft to depart from DFW, the recordings were examined to verify that the landing runways and any runways dependent on them were exclusively committed to arriving aircraft.

Radar tracks of aircraft on final approach normally do not extend to the threshold, and so the existing radar data were used to extrapolate aircraft flight paths to the most likely runway. A NASA Ames Research Center analysis code called AN (Ref. 4) was modified

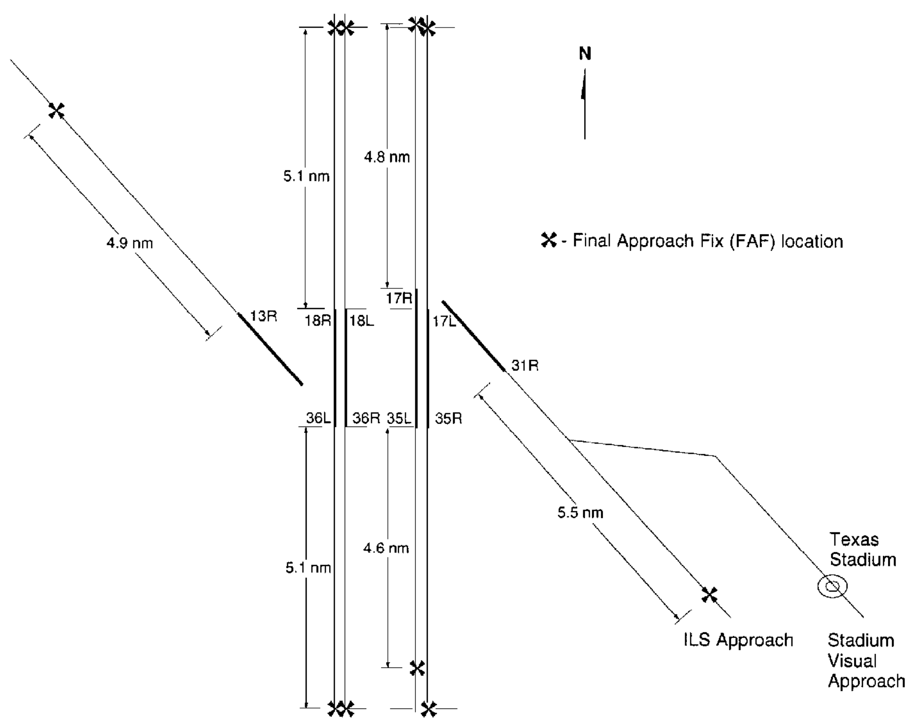

Fig. 1 Dallas/Fort Worth International Airport approaches (not to scale).

to provide estimates of the landing runway and threshold crossing time for each aircraft. The aircraft landing order for each runway was then determined, and threshold interarrival spacings and times were estimated. Whether they landed or not, all aircraft that were on the final approach course were treated as landing aircraft because they occupied a landing slot.

Separations Modeling and Analysis

Minimum separation constraints are most critical for the final approach flight segment, when all aircraft share a common approach path and the danger from wake turbulence is highest. Under VMC, the common path is typically about 6 n miles long at DFW; under IMC, final-approach-course intercept requirements result in a common approach path that is approximately 9 n miles long. A slow leading aircraft may be overtaken by a faster trailing aircraft, and so both aircraft must be spaced so that they will not violate the minimum requirements at the threshold. A fast leading aircraft will pull away from a slower trailing aircraft, and so minimum separation occurs before crossing the threshold.

A model of required separations was developed to convert required minimum separations that apply over the entire common approach path to required minima at the threshold. The model was also used to estimate the corresponding required threshold interarrival times. These threshold values were dependent on the length of the common path, the final approach trajectories of the leading and trailing aircraft, and the separation minima defined by the leading and trailing aircraft types. The threshold separation was defined as the separation when the leading aircraft crosses the threshold, determined such that no separation constraint was violated along the entire common path. The common path separation was defined similarly for the point when the trailing aircraft crosses the start of the common path. Figure 2 illustrates the distance and time separations as defined for the study. Two or more speeds are typically used on the common approach path, resulting in approach profile characteristics as shown in the figure. The minimum separation occurs between the common path start and the threshold, a situation that happens frequently.

The required-separations model categorized all aircraft types into six classes to distinguish among aircraft that have different required minimum separations or significantly different landing speeds. The speed/weight classes were 1) heavy aircraft, 2) large jets, 3) large turboprops and props, 4) small turboprops and jets, 5) small props, and 6) B757s. Representative approach profiles for the speed/weight classes and the two meteorological conditions were generated by CTAS. These approach profiles were adjusted based on the recorded data as explained in Ref. 2 and used in the following analysis.

Threshold separations associated with arrival rushes were analyzed statistically to document and understand current threshold spacing under high-demand arrival conditions. All records associated with weather conditions that required aircraft to follow the final approach course through the approach gate were included. Small props were not analyzed because the low frequency of small-prop landings at DFW resulted in a small sample size.

Figure 3 is a histogram of aircraft separation distances for all lead/trail combinations with 2.5-n mile required minimum separations. A probability density function with a smoothing window equal to the distance between the first and third quartiles is also shown. The vertical dashed line represents the minimum required separation. The distribution is asymmetric, with a maximum point corresponding to approximately 3.2 n miles and a tail extending to the right. The tail is caused by arrival gaps, which occurred because landing aircraft were not in position to follow a leading aircraft at the required minimum distance. Separations in 7.5% of the cases were smaller than the required instrument approach minimum.

The characteristic shown in the figure is representative of almost all the threshold separation distributions observed. It can be modeled as a combination of two parts, as in Ref. 5. The first part represents periods when aircraft are in position to land at the maximum runway capacity. It is modeled as a normal distribution of the positioning accuracy of the controller/pilot team. The second part represents the periods that contain excess separations caused by a lack of aircraft in position. It is represented by a convolution of the normal distribution with a Poisson distribution of the arrival gaps. Previous simulations of spacing accuracy support the normal distribution component of the model.[6] Because the recorded data are for periods of Center delay buildup, optimal management of terminal airspace under these conditions should result in normal distributions that represent controller/pilot accuracy only.

Because the maximum points of the distributions are generally to the right of the required minimum separation, controllers may have been (intentionally or unintentionally) adding extra separation

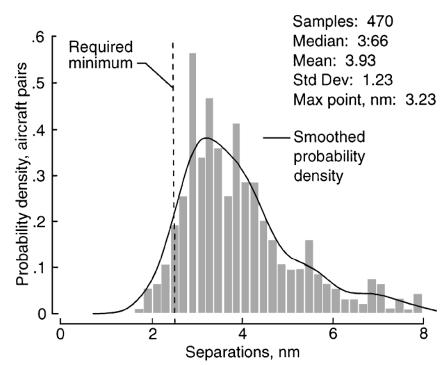

Fig. 3 Distribution of distance separations for all cases with 2.5-n mile required minimum separations.

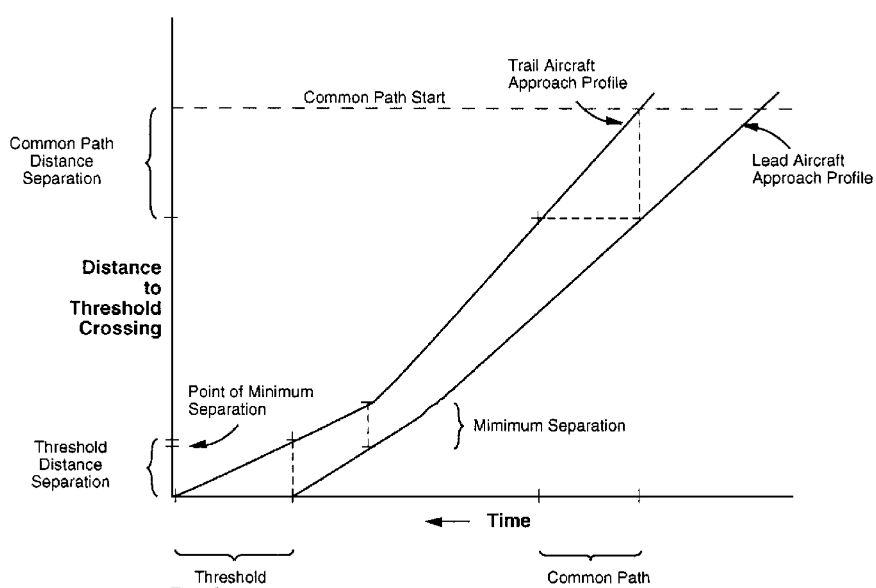

Fig. 2 Definitions of separations at the threshold and the beginning of the common path.

Table 2 Rush-period arrival spacing precision

Minimum required separation, n miles	Samples	Max point, excess n miles	Symmetric separation std dev, n miles	Symmetric separation std dev, s	Minimum separation fraction
2.5	470	0.7	0.64	19.6	0.09
3.0	323	0.1	0.53	19.6	0.38
4.0	112	0.4	0.86	25.5	0.33
5.0	50	−0.2	0.83	38.2	0.56
Simulation, Ref. 6[a]	514	0.31 (mean)	0.65	19.49	N/A

[a]Lumped subject data interarrival error for 170-knot manual pattern procedure. Arrival traffic weight class mix was made up of 87.5% large and 12.5% heavy, resulting in minimum required separations as follows: 87.5%–2.5 n miles; 1.5%–4 n miles; and 11%–5 n miles.

Table 3 Estimated controller target threshold crossing separations[a] in nautical miles (leading aircraft down, trailing aircraft across)

Aircraft speed/ weight class	Heavy	Large jet	Large turboprop	Small turboprop	B757
Heavy	4.2	5.2	5.6	6.2	5.2
Large jet	3.2	3.2	3.6	4.2	3.1
Large turboprop	3.1	3.1	3.2	4.2	3.1
Small turboprop	3.1	3.1	3.1	3.1	3.1
B757	4.2	4.2	4.2	5.2	4.2

[a]For conditions having a ceiling less than 3000 ft AGL or visibility less than 5 miles.

buffers to account for spacing imprecision. The distribution maximum point was used as an approximate measure of this aim point and as the mean of a symmetric distribution that would represent traffic flow with no arrival gaps. Table 2 compares results of the rush-period analysis, broken out by minimum required separation, and results of the simulations of Ref. 6 are also shown. The live data results tend to support the earlier simulation findings: for manually controlled traffic, standard deviations of interarrival time separation distributions are approximately 19 to 20 s for an arrival mix made up mostly of 2.5–n mile required separations. The table also shows that both spacing precision and controller buffers tend to decrease with increasing required minimum separation. The minimum separation fraction, defined as the fraction of symmetric distribution cases that have separations smaller than the required minimum, increased with increasing required minimum separation.

Target separations that may be used by the controllers were estimated from the statistics of each of the lead/trail speed/weight class combinations; they are summarized in Table 3 for instrument conditions. A potential benefit from terminal-area automation may be to improve spacing consistency on the final approach path, thereby allowing these controller target values to be reduced. Automation can accomplish this by providing the controller with clearance advisories to adjust aircraft ETAs through vectoring and speed changes.[7]

Runway Utilization and Capacity

An analysis of runway utilization and capacity was performed for all runways that were active during each of the 30 recorded rush periods. Spacings of individual aircraft pairs and the relationship of these spacings to each other were examined to identify usage trends. For each aircraft pair, interarrival distance and time separations were compared with the required threshold minima, which were computed using the required separations model. Because the closely spaced arrival/departure runways are dependent, each set was considered one effective runway for the analysis.

A graphical representation of threshold spacing as a function of time was developed to facilitate analysis. An example of the graphic, referred to herein as a threshold interarrival spacing plot, is shown in Fig. 4. Overall runway utilization can also be seen. Excess separations are represented as vertical bars attached to a horizontal zero line that corresponds to the minimum required separation at the runway threshold. Positive excess values represent cases for which additional runway landing rate could have been obtained by closing up spacings between aircraft. Negative values may or may not constitute separation violations, depending on whether or not the pilot has assumed responsibility for a visual approach. The numbers at the apex of each bar represent minimum required separations in n miles with respect to a leading aircraft, computed for the threshold.

Some simple computations were performed for each runway rush period to obtain conservative approximations of runway utilization and capacity, and results are shown in the figure for the analyzed runways. An aircraft landing rate was determined over the interval defined by the first leading aircraft and the last trailing aircraft, and results were adjusted to represent aircraft per hour. The average required minimum separation that included a 0.25–n mile separation buffer was also determined. The buffer was used to keep all capacity estimates conservative. An approximation was also made of the number of additional aircraft that could have landed per hour. The positive and negative excess separations were totaled to obtain a net excess for the rush period, which was adjusted to units of aircraft per hour. This result was divided by the average required minimum separation and limited to values greater than or equal to zero. This estimate is referred to in the following discussion as the additional aircraft calculation. A more commonly used alternative estimate of additional runway capacity was also used. It was obtained by calculating the maximum capacity with no excess separations and subtracting the actual landing rate from it. The maximum capacity was determined by inverting the time separation corresponding to the average required minimum separation for the rush period, including the buffer. The alternative estimate is more conservative because it assumes that no negative excess separations are acceptable.

A similar time history plot was generated for time separations. An example that corresponds to the rush period of Fig. 4 is shown in Fig. 5. In these threshold interarrival time plots, the vertical bars represent excess separation in seconds. For aircraft having positive excess times, the bold portion of each vertical bar represents the portion of excess separation that could have been removed because the aircraft was delayed in the Center. In the figure, all aircraft that were delayed had Center delays larger than the excess time separations, and so their corresponding vertical bars are entirely bold. As would be expected, the majority of aircraft landing during the rush periods were delayed in the Center.

The Center delay values associated with the bold vertical bars were summed to obtain a value of potential Center delay reduction. It is shown in the figure in units of seconds of Center delay per hour of rush period. Vertical bars corresponding to negative values are not considered in the computation; these aircraft could not land at an earlier time without reducing separations further below the required minima.

Although the delay reduction calculation is approximate, it may be a conservative estimate of the actual potential for reducing delays. If two or more aircraft with positive excess times and Center delays are in sequence, further delay reduction can be obtained by rescheduling the lead aircraft to land earlier, thereby increasing the excess time and delay reduction potential of the trailing aircraft. To obtain an approximation of the upper bound of delay reduction potential, the total of all positive delays incurred in the Center for all displayed aircraft is also provided in the figure.

Examples of Trends

Figure 4 corresponds to a rush period referred to as the noon balloon by DFW personnel; it lasted approximately 1 h, with an arrival type mix resulting in an average required minimum separation (with buffer) of about 3.6 n miles. The landing rate during this period was

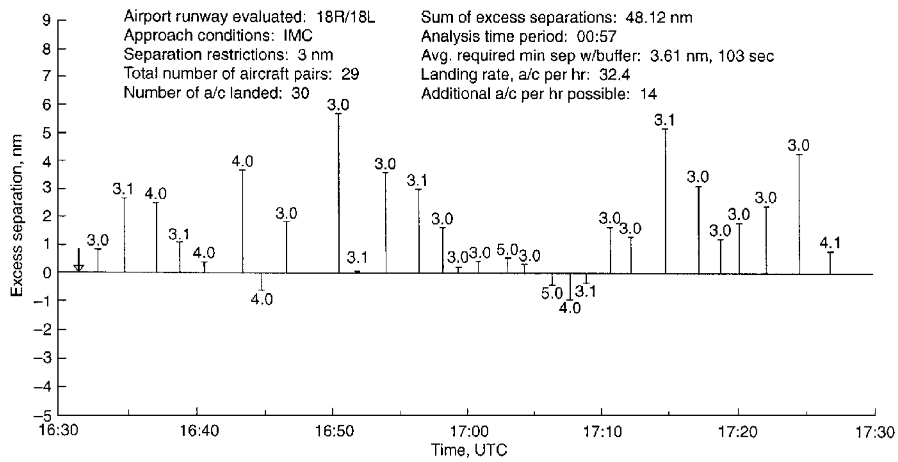

Fig. 4 Threshold interarrival spacing plot showing typical runway utilization during rush periods.

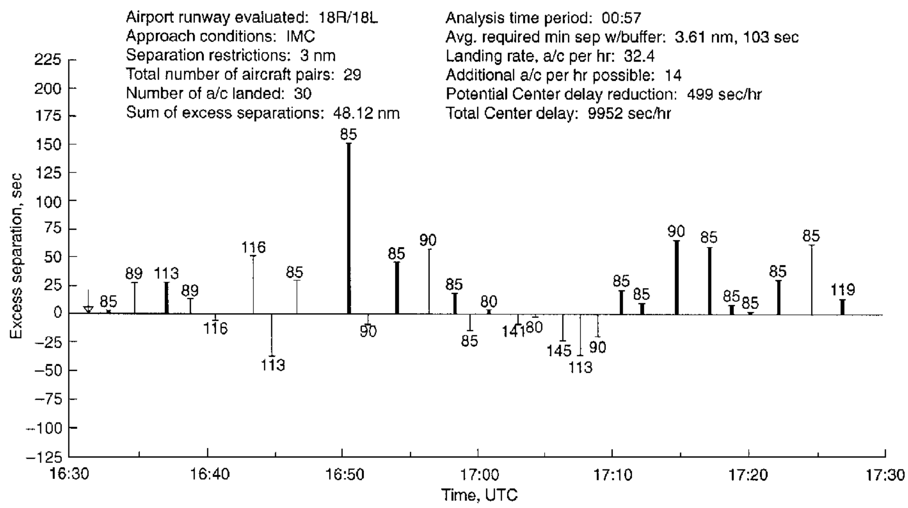

Fig. 5 Threshold interarrival time plot showing typical runway utilization during rush periods.

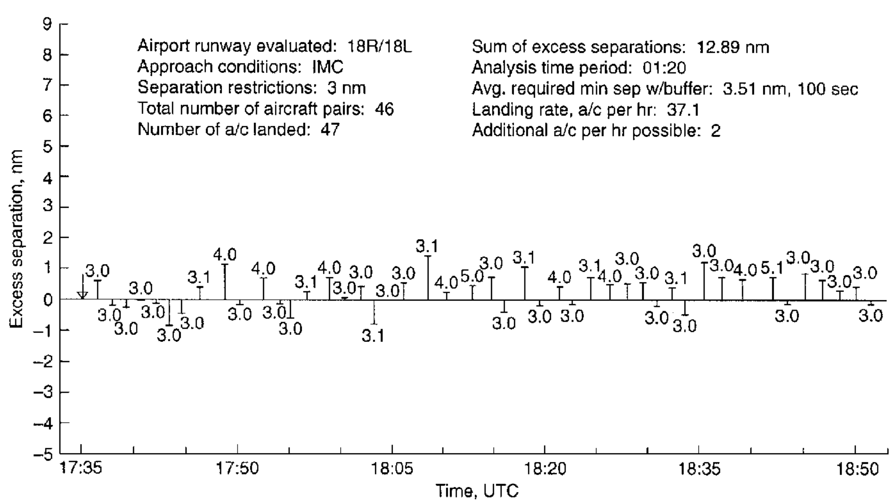

Fig. 6 Threshold interarrival spacing plot for a high runway utilization period.

about 32 aircraft per hour, and an additional 14 aircraft could have landed with no increase in negative excess separations. These values are typical of results seen for the north/south runways during IMC.

The correlation between this threshold interarrival spacing plot and the interarrival time plot of Fig. 5 is good: similar trends can be observed in both plots, an indication that the approach profiles extracted from the data are reasonably representative of flight times on the final approach segment for the various aircraft types.

In many cases, the large variations seen in the results may be attributable to variations in controller consistency. Figures 4 and 5 are good representations of typical IMC arrival separations in the observed data, and the performance measures shown are representative of the overall results for IMC. Large excess separations are observed, and a few small negative excess separations occur. Figures 6 and 7 represent a different noon balloon rush with very similar meteorological conditions. In the latter rush, very accurate separations are maintained between aircraft; the landing rate is high, and the number of additional aircraft able to land is very small. Because of the high runway utilization, the potential for Center delay reduction has been lowered by 35%. If the recorded data set is considered a basis

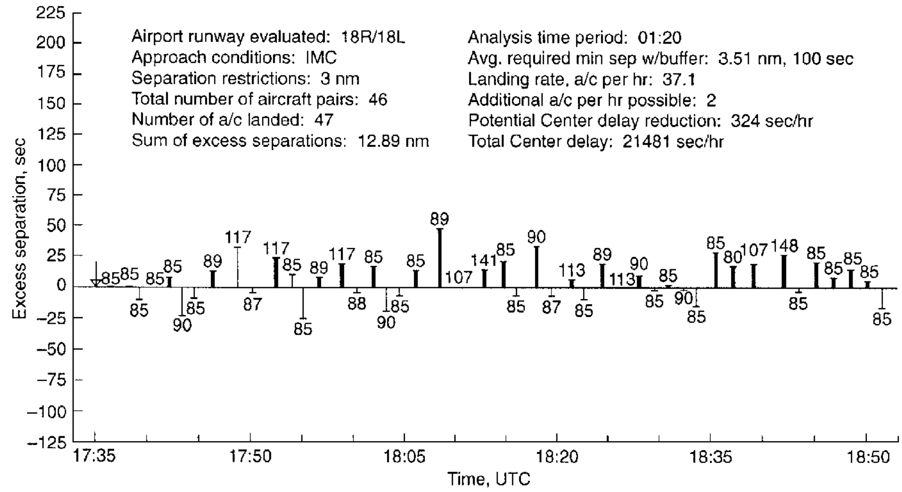

Fig. 7 Threshold interarrival time plot for a high runway utilization period.

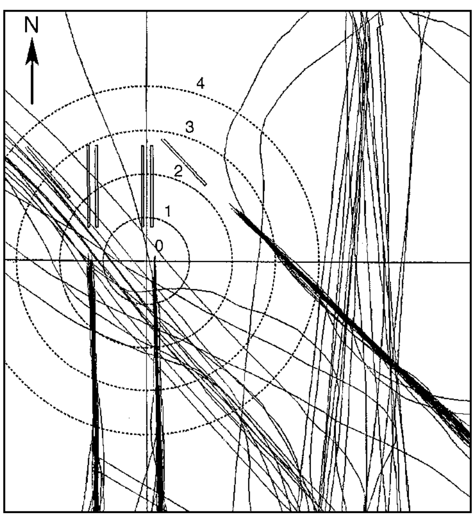

Fig. 8 Example of radar tracks during instrument meteorological conditions.

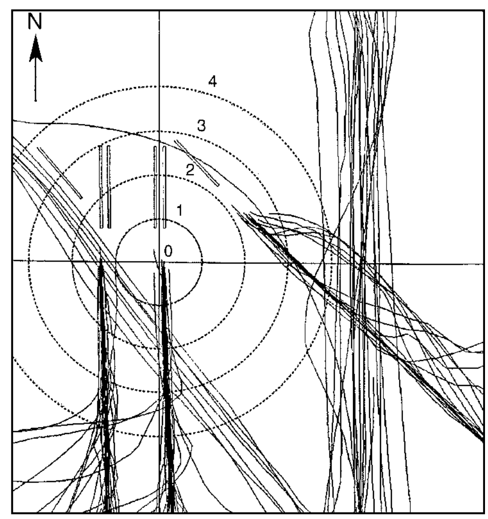

Fig. 9 Example of radar tracks during visual meteorological conditions.

for judgment, the latter rush represents excellent runway utilization by manual control. For both rushes, there was significant delay buildup in the Center. These large differences in runway utilization observed for similar conditions suggest that automation may improve the consistency of traffic management. Because the highest observed performance was quite high, a potential exists to improve performance for all controllers at least to this level.

Meteorological conditions on approach impact the practices of pilots and procedures followed by pilots and controllers. Some of these differences in the procedures can be seen by comparing radar tracks of rush periods for conditions better than 3000-ft ceiling/5-mile visibility with those under poorer conditions. Figure 8 is an example of north-flow arrivals during poor conditions. The airport ceiling was reported to be 1000 ft AGL with 5-mile visibility, and there was no precipitation. Most of the aircraft tracks are seen to be straight and lined up with the landing runways; they are tightly grouped laterally as they approach the runway thresholds, and no aircraft are reassigned to the inboard (departure) north/south runways. Figure 9 shows a similar rush period that occurred during good weather conditions. There was no ceiling, and the visibility was 15 miles. Some aircraft are seen to turn on to the final approach course as late as 4 n miles from the threshold. For Runway 31R, the stadium visual approach was in effect for some aircraft. The tracks also display much larger deviations from the runway centerline near the runway threshold, and some aircraft were directed to land on the inboard north/south runways.

These differences in weather conditions cause differences in landing separation characteristics. During poor conditions, aircraft tend to be evenly spaced, with only a few slightly negative excess separations; during good weather, aircraft are less evenly spaced, and there are more negative excess separations. The use of inboard runways for arrivals, the efficient utilization of runways by turboprops, and spacing discretion of pilots conducting visual approaches all contribute to the landing separation characteristics observed during VMC. These characteristics led to a significant potential for capacity improvement, as discussed next.

Potential for Capacity Improvement and Delay Reduction

Observed runway landing rates are shown in Table 4 for the two weather conditions. Landing rates were greater under VMC than under IMC because visual approaches result in a higher frequency of negative excess separations. Wide ranges of runway utilization were observed during rush periods, with landing rates as low as 16 aircraft/h and as high as 48 aircraft/h. Landing rates for the diagonal runways were also found to be much lower than for the north/south parallel runways. When shown these unexpected results, controllers stated they were not aware of favoring the north/south runways and that the observed differences were not caused by runway assignment preferences of pilots or controllers. They also knew of no airspace design factors that would cause the diagonals to be underutilized. These results suggest that runway load balancing, even for the relatively straightforward three-runway configurations of DFW, is a difficult task to perform manually.

The results show that significant capacity increases are possible at DFW. The maximum runway capacity was found to be approximately 50 aircraft/h using the additional aircraft calculation and

Table 4 Observed runway landing rates

Condition	North/south runways, aircraft/h	Diagonal runways, aircraft/h
IMC	33.6	25.7
VMC	37.8	31.2

Table 5 Capacity increases possible, assuming zero-excess separations and a controller buffer of 0.25 n miles

Condition	Capacity increase per runway	North/south runways	Diagonal runways
IMC	Mean, aircraft/h	4.1	10.1
	Increase, %	12.2	39.2
VMC	Mean, aircraft/h	4.3	10.7
	Increase, %	11.3	34.4

about 40 aircraft/h using the more conservative zero-excess separations calculation. The number of additional aircraft that could have landed ranged from an average of 12 aircraft/runway-h for north/south runways to more than 20 aircraft/runway-h for the diagonal runways.

Table 5 summarizes the capacity increases possible using the zero-excess separations capacity estimate. Large improvements from automation may be expected through better runway balancing, thereby enabling higher utilization of the diagonal runways. The table indicates that these capacity improvements should be possible under both IMC and VMC. In fact, the analysis showed that, for an equal number of operating runways, capacity improvement potential is not strongly affected by meteorological conditions. The conservative zero-excess measure resulted in an overall airport capacity improvement potential of 15%, whereas the additional aircraft calculation resulted in an improvement potential of 36%.

The results also showed that approximately 1200 s of Center delay per airport rush hour can be reduced by removing the unnecessary excess separations. Using the direct-operating-cost estimates of Ref. 8, this translates to a cost saving of about $2.2 million per year at DFW, assuming that no other factors prevent the airport from handling the increased landing capacity. Additional delay reduction can be expected through optimal runway assignment and by resequencing aircraft to some optimal landing order.

Conclusions

A method has been developed for determining interarrival spacing between aircraft pairs on final approach and estimating capacity under actual operational conditions. An analysis using the method indicates that there is a large potential for utilizing runways more effectively through improved management of aircraft in terminal airspace. Terminal area decision support tools such as CTAS should assist controllers in achieving this potential. A significant capacity increase can be achieved through improved balancing of runway loads. Additional increases can be obtained by spacing aircraft on final approach to prevent missed landing opportunities and by providing spacing precision that enables controller spacing buffers to be reduced. Potential benefits include lowered operating costs for airport users and a reduced need for future airport expansions.

Improvements from terminal area automation can be expected at most airports for which arrival demand approaches or exceeds capacity. Airports similar to DFW, which operates up to three independent runways dedicated to arrivals and contains an aircraft mix dominated by heavy jets, large jets, and large turboprops, will experience throughput improvements of 15% or more during arrival rush periods. These improvements will not be strongly affected by meteorological conditions. For traffic flying into DFW, benefits will probably be measured in terms of millions of dollars in direct-operating-cost savings per year. Airports containing dependent arrival runways, runways that must also serve departures during rushes, or more diverse aircraft type mixes may require more sophisticated decision support automation than DFW, but because their operations are more complex, they should ultimately achieve even greater benefits.

Acknowledgments

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