Departure Efficiency Benefits of Terminal RNAV Operations at Dallas-Fort Worth International Airport

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On September 6, 2005 the Federal Aviation Administration (FAA) implemented revised Standard Instrument Departure (SID) procedures at Dallas-Fort Worth International Airport (DFW). The procedures leverage Area Navigation (RNAV) capabilities that enable greater flexibility and accuracy in point-to-point navigation. Implementation of the procedures relies on flight automation systems currently available on the majority of commercial and corporate aircraft and promises more efficient utilization of available runways and constrained airspace surrounding the airport. This paper outlines the design of DFW's RNAV departure procedures and reviews the mechanism that enables operational benefits. It describes the Monte Carlo modeling approach taken to evaluate operational changes, the methodology used to validate model performance with radar data, and presents potential departure capacity and delay reduction benefits of RNAV departure operations at DFW. It shows that delay reduction benefits to users and operators of close to $10 million annually are possible for DFW when conducting RNAV departure operations. Key performance metrics of the model are compared to performance metrics obtained from extensive pre- and post-implementation evaluations. They confirm that the required operational changes that enable delay reduction benefits were largely realized within the first 2 months after implementation of the procedures.

I. Introduction

Conventional navigation concepts that currently apply in terminal operations in the vicinity of most major U.S. airports largely rely on Air Traffic Control (ATC) providing routine navigational guidance. On September 6, 2005 the FAA implemented departure procedures at DFW that leverage greater flexibility and navigation accuracy of RNAV procedures for navigational guidance in terminal airspace. The implementation of RNAV procedures at DFW and other airports represents an enhancement from conventional navigation concepts. It aims to leverage on-board navigation capabilities of advanced flight automation systems in terminal operations. Such RNAV procedures are key building blocks in the FAA's plan to integrate advanced navigation methods in the U.S. National Airspace System (NAS).[1] Implementation of RNAV procedures represents a significant milestone toward realization of a performance-based navigation concept as outlined in the FAA's Operational Evolution Plan (OEP).[2] The plan calls for the development of standards for Required Navigation Performance procedures (RNP) as part of worldwide efforts to develop and implement the next generation of communication, navigation, and surveillance systems in air traffic management (ATM). The accuracy of RNP and its integrity monitoring capability are expected to further enhance the navigational precision of RNAV and define aircraft flight paths within tightly specified airspace corridors.

A. Conventional Departure Operations

Conventional departure operations rely exclusively on course guidance instructions provided by ATC. In terminal airspace, these control instructions typically comprise sequential assignments of aircraft headings that are issued to departing flights via voice communications. Timely issuance of successive clearances instructing flight crews to fly assigned headings commonly referred to as *vectoring* serves as a key control mechanism to continually ensure aircraft separation and to provide navigational guidance to points typically located about 40 nautical miles (NM) from the airport. These navigational points are often referred to as *departure fixes.* In conventional departure operations at DFW, aircraft reliance on on-board navigational course guidance is generally delayed until aircraft approach or cross a departure fix approximately located at the lateral boundary between terminal and en-route

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airspace. Figure 1 illustrates the octagonal shape of DFW's terminal airspace boundary and the locations of 16 departure fixes that are indicated by triangles.

B. RNAV Departure Operations

RNAV departure operations now in use at DFW represent a significant enhancement to conventional operations. Reliance on on-board navigational equipment begins soon after takeoff. A series of waypoints that define each RNAV route – commencing close to the departure end of each runway and comprising a departure fix at the airspace boundary – is the basis for aircraft course guidance of RNAV operations in the terminal area. The lateral paths of DFW's RNAV departure routes are illustrated in Fig. 1.

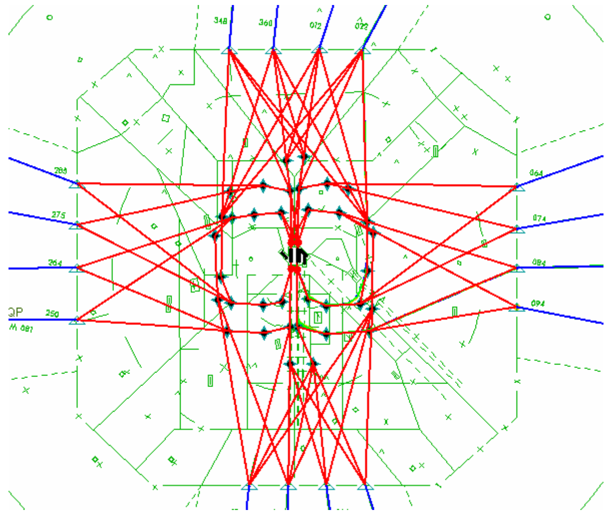


Figure 1. Key features of DFW terminal airspace (green) and route structure of RNAV departure procedures (red).

For a given route and aircraft operating conditions, the on-board Flight Management Systems (FMS) of departing aircraft that utilize RNAV procedures derive and execute automated navigation solutions guiding aircraft along the various path segments defined by the procedures. The procedures feature two initial segments with diverging courses from each primary runway. A sub-set of the procedures that serves a certain group of departure fixes initially follows courses along the extended runway centerlines, effectively mirroring straight-out conventional departure operations. Other procedures feature courses that initially diverge from the extended centerlines by an angle of 15 degrees or more. Figure 2 illustrates the course divergence which is a key design feature that spreads departure traffic flows across the terminal airspace and enables ATC to make more efficient use of DFW's constrained airspace and runway capacity. Implementation of the procedures and ATC sequencing of successive flights to make alternating use of diverging RNAV routes have promised increased airport departure capacity, improved throughput, and reduced delay.

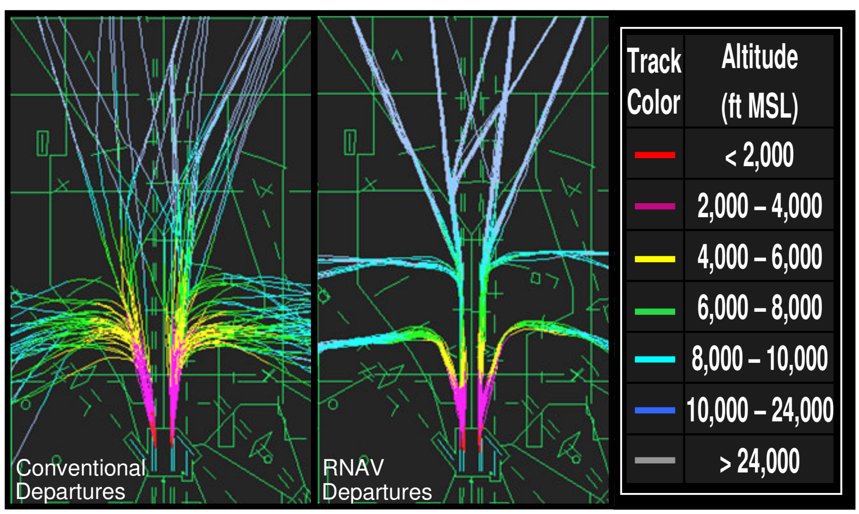


Figure 2. Radar tracks recorded during times of peak departure demand of aircraft departing DFW before and after implementation of RNAV procedures.

The research reported in this paper was carried in support of the FAA's RNAV/RNP Program Office during design and implementation of RNAV departure procedures at DFW. Key procedure design considerations are reviewed in Section II and the mechanism that enables operational benefits of DFW's RNAV departure operations is outlined in Section III. Section IV presents the results of a Monte Carlo model simulation analysis quantifying potential capacity gains and delay reduction benefits, and the results of post-implementation operational evaluations are discussed in Section V.

II. Procedure Design and Implementation

A key objective in the design of DFW's RNAV departure procedures was to increase airport departure capacity. For this reason, the RNAV route design was chosen to feature course divergence of initial route segments which effectively results in departure flows that are more spread-out across the terminal airspace (see Fig. 2). Key design specifications resulted from the requirement that terminal traffic patterns conform to previously established environmental constraints and the need to accommodate local traffic flows serving satellite airports. In the past, these constraints in conjunction with larger operational uncertainties typically associated with vectored operations precluded conducting fanned departure operations, i.e. operations that routinely employ application of diverging departure headings. The reduced operational uncertainty generally associated with RNAV operations was found to support the design of two diverging RNAV route segments from each runway that meet established noise-footprint requirements. At the time of procedure implementation, about 84 percent of all aircraft were anticipated to be appropriately equipped and participating in RNAV operations. The resulting need of the airport to conduct mixed-equipage operations was expected to represent the most significant ATC operational issue associated with the implementation. Addressing this issue involved identification of non-RNAV aircraft based on available flight planning information and application of conventional ATC services to non-participating aircraft. Conventional traffic flows especially of East- and West-bound departures effectively represent additional third departure flows typically located within the bounds of the two RNAV routes defined by the procedures (see Fig. 2). In order to address the ATC operational issues resulting from RNAV and non-RNAV aircraft sharing the same departure corridors and the greater operational uncertainties associated with vectored operations, DFW Air Traffic Control Tower (ATCT) anticipated the need to apply additional spacing when clearing successive RNAV and non-RNAV aircraft for departure. This need for additional spacing in mixed-equipage operations arises only if a leading or trailing RNAV departure involves certain routes. The frequency of application of additional spacing can be expected to decrease in the future as RNAV equipage increases and more aircraft are authorized to participate in terminal RNAV operations.

III. Benefit Mechanism

Key operational changes that result from the design and implementation of RNAV departure procedures at DFW are illustrated in Fig. 3. These operational changes are associated with the diverging initial route segments the procedures provide for navigation soon after takeoff. The figure compares a typical initial flight pattern of conventional operations involving single flows of aircraft from parallel departure runway to the pattern of RNAV departure operations on two initially diverging route segments. If aircraft that are lining up for departure at a runway can be queued in separate line-up queues (serving initially diverging RNAV routes), the separate queues enable ATC to efficiently sequence aircraft for diverging departures, i.e. departure operations that make alternating use of initially diverging routes.

The mechanism that enables operational benefit of diverging departure operations is based on differences in ATC minimum separation standards that apply to straight-out and diverging departure operations.[3,4] The minimum ATC separation standard that applies most frequently to consecutively departing aircraft operating at large U.S. airports, i.e. *Radar Separation*, calls for an initial application of 3-nautical mile (NM) spacing between straight-out departures.[3] If the same aircraft can be sequenced for diverging operations and *Same Runway Separation* standards can be applied, a subsequent departure start the takeoff roll if the preceding departure has gained a distance of 6,000 feet and has become airborne.[4] Thus, applicable ATC minimum standards for diverging departure operations generally impose a less

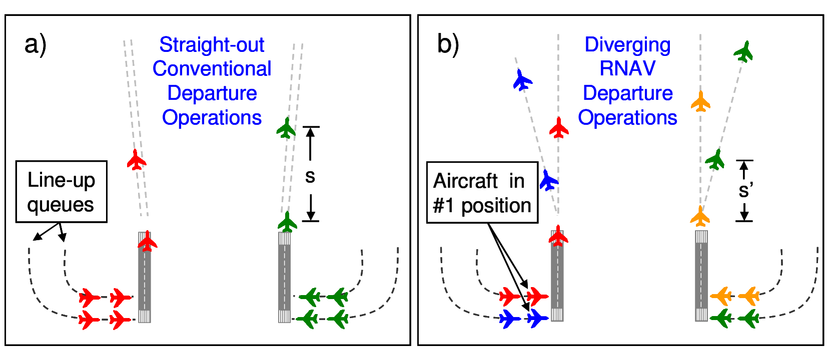


Figure 3. Illustration of (a) conventional and (b) RNAV departure operations at DFW.

stringent constraint and enable ATC to effectively reduce inter-operation times between aircraft departing on diverging courses. The associated gain in departure efficiency can be expected to result in improved departure performance of the airport.

IV. Monte Carlo Simulation Analysis

Computer simulations of air traffic are a major source of quantified estimates of system benefits that can arise from the implementation of procedural changes. The MITRE Corporation's Center for Advanced Aviation Systems Development (CAASD) was tasked to support the FAA in evaluating potential benefits of proposed operational changes and developed fast-time simulation capabilities. The modeling process that was applied to evaluate benefits resulting from the implementation of RNAV departure operations is outlined in Fig. 4. Key features of the modeling capabilities include (1) data-driven validation of the simulation model, (2) an agent-based modeling platform, and (3) Monte Carlo modeling techniques. A detailed description of the modeling capabilities is given in Ref. 5.

The gain in departure efficiency that results from conducting diverging departure operations is evidenced by reduced inter-operation times between aircraft departing on diverging courses. Thus, the time effectively applied between departures (subsequently referred to as *inter-departure time* or *departure interval*) serves as key metric to quantify operational changes associated with diverging operations and improvements in departure efficiency. This metric was also used to validate the baseline model of conventional departure operations described in the following section.

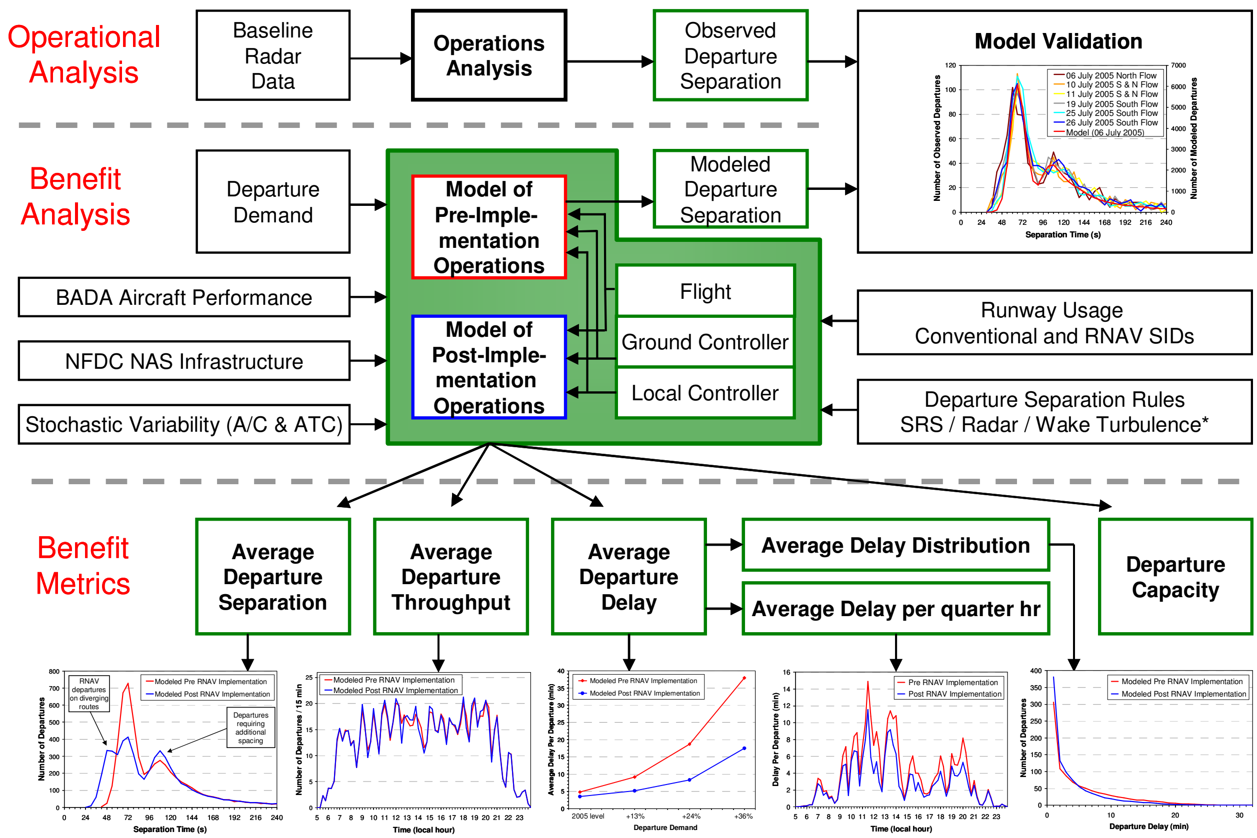


Figure 4. Key features of the iTRAEC modeling capabilities employed to evaluate benefits of RNAV departure operations.[5]

A. Model Validation of Conventional Operations

Radar track data recorded during six days of conventional operations conducted in visual meteorological conditions (VMC) in the weeks preceding the implementation of RNAV departure procedures were analyzed and inter-departure times (or *departure intervals*) were extracted for each pair of departing aircraft. For each day of operations, the measured inter-departure times were counted in bins of 6-second width to obtain distributions of inter-departure times. Thus, the distributions illustrate how often inter-departure times fell within six-second time intervals extending over the whole range of measured values. Figure 5 presents inter-departure time distributions extracted from radar track data of actual operations. Each observed distribution comprises nearly 1000 separation measurements of actual departure operations. It is interesting to note common features as well as the appreciable day-to-day variability displayed in the various distributions. This observation can be viewed as evidence of the presence of operational constraints in addition to the constraints associated with ATC's implementation of applicable separation standards including limited voice communications capacity, air crew procedural requirements that result in actuation delays, controller/flight crew style, workload, and performance (see Ref. 5). A key feature shared by all distributions is that the mode (or peak) of the distributions can be seen at about 60 to 70 seconds of inter-departure time. This most frequently observed inter-departure time is consistent with applicable ATC Radar Separation standards requiring an initial 3-nautical mile (NM) spacing between straight-out departures. Other features of the distributions starting at about 70 to 80 seconds of inter-departure time can be associated with operations requiring application of wake turbulence separation standards (involving initial 4 and 5 NM spacing between departures), runway crossing operations (arriving aircraft routinely cross departure runways when taxiing to the gates), and operations during time periods of low departure demand.

The model of conventional departure operations employed aircraft flight plan and push-back information derived from Enhanced Traffic Management System (ETMS) data. The departure demand data of one day of DFW operations was selected to represent an average-day demand scenario. In order to extend the validity of the model beyond the single day represented in the departure demand data, the Monte Carlo model introduced stochastic variations in the times aircraft were scheduled to push back from their gates. Multiple replicates of Monte Carlo runs were executed and mean values of model metrics were obtained representing the statistics of 50 days of operations totaling about 50,000 simulated operations per simulated scenario. Figure 5 compares the distributions associated with operations observed during six days of actual operations and the average distribution of inter-departure times obtained from the validated model of conventional departure operations. The comparison indicates generally good agreement between actual and modeled operations suggesting that significant constraints intrinsic to actual operations are sufficiently accounted for in the model. The performance of the validated model served as a performance baseline for comparing RNAV operational alternatives and estimating potential benefits of RNAV departure operations.

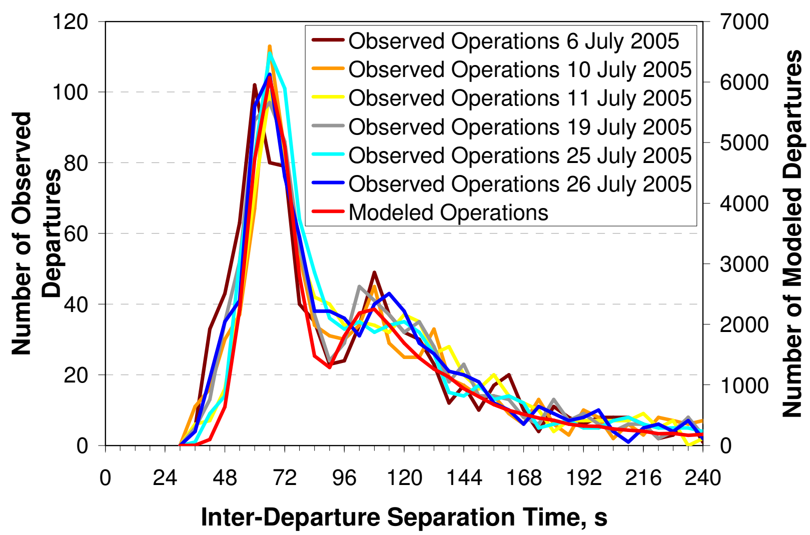


Figure 5. Comparison of observed and modeled inter-departure time distributions.

B. Model Evaluation of RNAV Operations

When evaluating potential benefits of RNAV departure procedures, the alternative model of proposed operations differs from the model of conventional operations insofar as it employs procedural constraints that are adapted to reflect operational changes associated with implementation of the proposed procedures. These constraints include the leveraging of opportunities to sequence aircraft for diverging departures (see Section III) as well as applying applicable separation standards between all combinations of departures that make sequential or alternating use of straight-out or initially diverging RNAV departure routes (see Fig. 3).

As stated above, the distribution of separation times that are effectively applied between departures (inter-departure times) was identified as a key metric quantifying changes in departure efficiency. Figure 6 presents the inter-departure time distribution of the validated model of straight-out conventional departure operations (red) and post-implementation operations (blue) that include diverging RNAV departure operations. These distributions of inter-departure separation times illustrate the impact of operational changes that can be expected to be associated with the implementation of DFW's RNAV departure procedures. The pronounced mode or peak of the distribution representing conventional operations that are separated according to *Radar Separation* standards resulting in 60 to 70 seconds of inter-departure time is seen to be essentially split in two components indicating a sizable number of diverging departures that is separated according to *Same Runway Separation* standards and spaced more closely at about 40 to 50 seconds.

It is interesting to note that the distribution associated with post-implementation operations also features an increased number of departures spaced about 100 to 110 seconds apart. This operational change reflects the impact of mixed-equipage operations that required application of additional spacing in some cases involving consecutive RNAV and non-RNAV departures departing via certain combinations of departure fixes (see Section II).

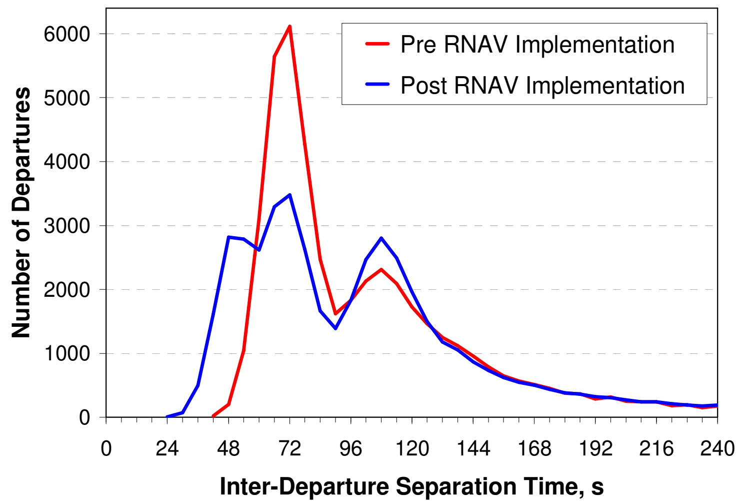


Figure 6. Inter-departure time distributions of the validated baseline model of conventional operations and of the model of post-implementation operations including diverging RNAV departures.

1. *Departure Capacity Benefits*

Capacity is commonly used as metric estimating the average number of operations an airport can conduct in a given time interval that is largely independent of the temporal distribution of demand. Thus, capacity modeling generally evaluates a scenario involving continuous departure demand. It provides an estimate of maximum sustainable throughput, on a long-term basis, given sustained demand.[6] Adopting the modeling capability to provide sustained departure demand, the gain in departure capacity due to – when possible – conducting diverging departure operations can be used to characterize the capacity impact of operational changes associated with implementation of RNAV departure procedures.

The results of the Monte Carlo simulation model analysis suggest a potential for significant departure capacity benefits at DFW. A capacity benefit of 11 additional departure operations per hour was found for DFW's fleet mix and RNAV equipage currently enabling about 84 percent of departures to participate in RNAV operations. The modeling also allowed estimating potential future capacity gains that could result if RNAV equipment levels were to rise and RNAV participation rates were to increase to full participation. Eliminating all mixed-equipage operations at DFW and assuming a RNAV participation rate of 100 percent, the results of the capacity model analysis were found to suggest that capacity gains of up to 20 additional departure operations would be possible for the airport.

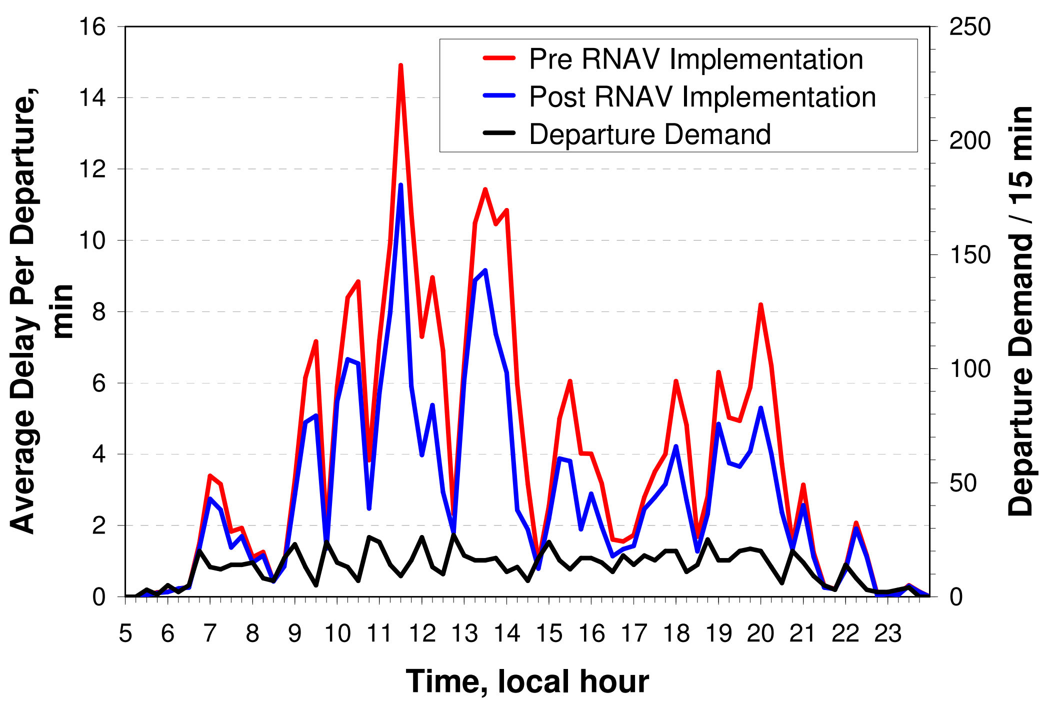
2. *Departure Delay Benefits*

Gains in departure capacity can be expected to give rise to improvements in departure efficiency enabling more operations during time periods with sustained departure demand. During these time periods, the ability to conduct more operations entails that aircraft that are lined up for departure at the runway often need to wait less time to obtain takeoff clearance. This is because of ATC's ability to sequence aircraft for departure to make alternating use of diverging RNAV routes which results in reduced inter-departure times when compared to conventional operations comprising sequential straight-out departures (see Section III).

The Monte Carlo simulation model was used to estimate potential reductions in departure delay associated with the implementation of RNAV departure procedures at DFW. In the model, departure delay was defined as any time an aircraft remained in a line-up queue at a runway (see Fig. 3). In other words, an aircraft accrued departure delay starting the moment it completed taxiing to the runway or when joining the line-up queue that has formed there and until it started to roll for takeoff. Multiple replicates of Monte Carlo runs were executed and mean values of departure delay were obtained representing the statistics of 50 days of operations totaling about 50,000 simulated operations per simulated scenario.

Figure 7 presents average departure delays of modeled operations. The average delays are based on 15-minute time intervals and the histogram shown represents results for all 15-minute time periods between the times of 0500 and 2400 local time. The figure also shows departure demand (per 15-minute time interval and at the time aircraft were modeled to push back from their gates) that was input to the model. Sustained departure demand is seen to have existed in two consecutive 15-minute time periods from about 19:45 to 11:15 local time which is seen to result in the greatest modeled departure delays in a half-hour period starting at about 11:15 local time. Comparisons of pre- and post-implementation departure delays were used to estimate potential reductions in departure delay associated with the implementation of RNAV departure procedures. For instance, the 15-minute time period starting at 11:30 local time is seen to yield the greatest reduction in average departure delay. During this time interval, the modeling results suggest an average delay reduction of 4.8 minutes per departure. Considering all flights during the entire day of modeled departure operations, the average departure delay was found to decrease from 4.8 minutes in conventional operations to 3.5 minutes in post-RNAV implementation operations. These results of the delay model analysis suggest an average delay reduction benefit of 1.3 minutes per departure.

Figure 8 presents average delay estimates obtained from the Monte Carlo simulation model of pre- and post-implementation operations at various levels of departure demand. The differences between pre- and post-implementation departure delays may serve to estimate the benefit potential associated with the implementation of RNAV departure procedures. As stated above, the modeling results were found to suggest a difference between average pre- and post-implementation delays of 1.3 minutes per departure at the 2005 level of departure demand. The figure also illustrates model estimates of the impact of increased departure demand on departure delay. A 13-percent increase in departure demand is seen to result in significant increases in departure delay, especially if the airport continues to conduct conventional departure operations. On the other hand, these results also suggest that delay can be expected to increase more slowly if post-implementation operations involving diverging departures can



7. Modeled airport departure delay per 15-minute time interval and departure demand (2005 level).

be employed. It is noted that average departure delays per aircraft, particularly at the 2005+36% demand level, may exceed values that would likely trigger adaptive actions by users and passengers and limit traffic growth rates.[7] The model presented here does not attempt to anticipate possible adaptive actions. Consequently, delay benefits should be considered progressively less reliable as departure delays increase and adaptive actions become more likely.

3. Cost Savings to Operators

Estimates of potential cost savings to airline operators that are associated with the implementation of RNAV departure procedures at DFW presented here are based on the differences between modeled pre- and post-implementation departure delays. As stated above, modeled post-implementation departure operations were found to accrue – on average – 1.3 minutes less delay per departure at the 2005 level of departure demand (see Fig. 8). This reduction in departure delay can be expected to result in reduced airline operating costs as aircraft would spend less time during ground operations while awaiting ATC takeoff clearance.

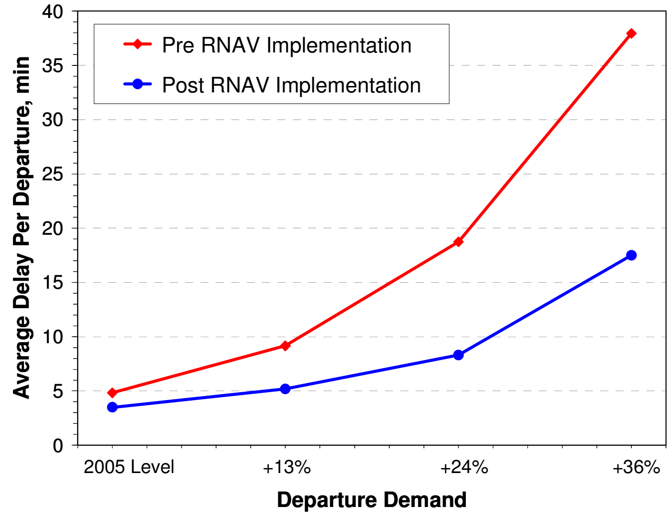


Figure 8. Modeled average departure delay associated with pre-RNAV implementation (red) and post-RNAV implementation (blue) operations (84 percent RNAV participation rate).

Cost benefits were derived from delay reduction benefits illustrated in Fig. 8 and Aircraft Direct Operating Cost (ADOC) values. An ADOC estimate for taxi operations of $22.24 per minute was adopted. This CAASD estimate is based on FAA APO guidance for estimating aircraft operating costs and 2005 fleet mix data for DFW.[8] Annual cost benefits were conservatively estimated by assuming that diverging departure operations can be conducted during 80 percent of 365 days. Furthermore, the annual impact of mixed-equipage operations was estimated by evaluating various levels of modeled RNAV participation rates. In addition to the current RNAV participation rate of 84 percent, the model allowed estimating annual cost benefits associated with varying RNAV participation rates. Figure 9 illustrates the annual cost benefit estimates associated with the implementation of RNAV departure procedures at DFW. At the 2005 level of departure demand, the results of the benefit model analysis were found to suggest annual cost benefits of $8.5 million for operators at the airport. A summary of the results is presented in Table 1.

The results of the model analysis also enable estimating the cost impact associated with partial RNAV equipage of the aircraft fleet operating at DFW. Assuming a RNAV participation rate of 84 percent, the cost benefit results summarized in Table 1 suggest an annual impact of over $4 million associated with conducting mixed RNAV/non-RNAV operations at the 2005 level of departure demand. This cost impact was found to increase significantly to over $10 million annually if departure demand is assumed to increase 13 percent above the 2005 demand level as shown in Table 1.

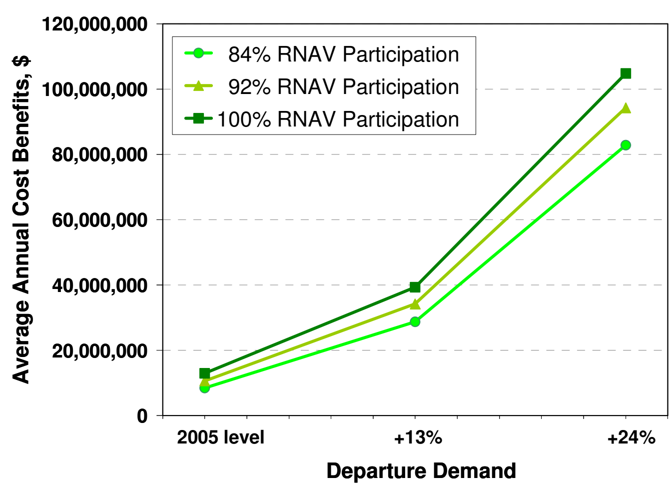


Figure 9. Annual cost benefit estimates of post-RNAV implementation operations at DFW.

Table 1. Annual cost benefit estimates of post-RNAV implementation operations at DFW.

RNAV Participation Rate (%)	Delay Reduction Benefit (Million $)		
	2005 Level of Departure Demand	2005 Level + 13%	2005 Level +24%
84	8.5	28.7	82.8
92	10.6	34.2	94.3
100	12.9	39.3	104.8

V. Post-Implementation Evaluation

Post-implementation evaluations were carried out in order to validate model estimates of operational changes associated with the implementation of the procedures. As discussed above, a key operational change that resulted from the design and implementation of RNAV departure procedures is associated with diverging initial route segments the procedures provide for navigation soon after takeoff. If aircraft that are lining up for departure at a runway can be queued for diverging departures (see Section III), applicable ATC minimum separation standards often enable application of effectively reduced inter-operation times between such aircraft. The metric that was introduced to characterize the resulting gain in departure efficiency is the distribution of inter-departure times (see Section IV).

The Monte Carlo model evaluation of the efficiency of DFW departure operations was found to suggest the potential for significant gains in departure efficiency (see Fig. 6). The model predictions of these gains were based on two key assumptions: (1) the departure sequence of two aircraft that have lined up at a runway and have advanced to *#1-Position* in their line-up queues (see Fig. 3) can be optimized at an 80-percent rate and (2) ATC workload considerations have no impact on the expediency of issuing takeoff clearances with an operational variability that is similar to that observed in conventional departure operations. The objective of the post-implementation evaluation was to validate these assumptions and the gains in departure efficiency predicted by the Monte Carlo model of post-implementation operations.

Post-implementation evaluations were carried out approximately one month and two months after implementation of the RNAV procedures at DFW.[9] The two-month time frame was considered sufficient to allow controllers working the Local Control positions in DFW's air traffic control towers to become familiar with the procedures and proficient in implementing the required operational changes. For each evaluation, radar track data recorded during six days of operations conducted in visual meteorological conditions (VMC) were analyzed and inter-departure times were extracted.

Figure 10 presents inter-departure time distributions extracted from radar track data of actual operations recorded about 1 month and 2 months after implementation of RNAV departure procedures. Each observed distribution comprises nearly 6000 separation measurements of actual departure operations. Figure 10 also shows the validated pre-implementation distribution of modeled conventional departure operations (red) as well as the distribution predicted by the Monte Carlo simulation model of post-RNAV implementation operations (green) previously presented in Fig. 6.

The results of the 1-month post-implementation evaluations (Fig. 10a) demonstrate the significance of the operational changes associated with the implementation of RNAV departure operations at DFW. The mode of the pre-implementation distribution that mainly characterizes the application of Radar Separation standards between consecutive departures (see Section IV B) is observed to be represented by a wider post-implementation distribution. The post-implementation distribution includes a significant number of smaller departure intervals (in the 40 to 60 second time frame) characteristic of application of Same Runway Separation standards. This number is seen to increase in operations recorded 2 months after implementation of the RNAV procedures shown in Fig. 10b) resulting in improved agreement between the shapes of the observed post-implementation distribution and the distribution predicted by the model. As this part of the distribution mainly represents ATC's application of *Same Runway Separation* standards to qualifying departures utilizing diverging RNAV route segments, the generally good

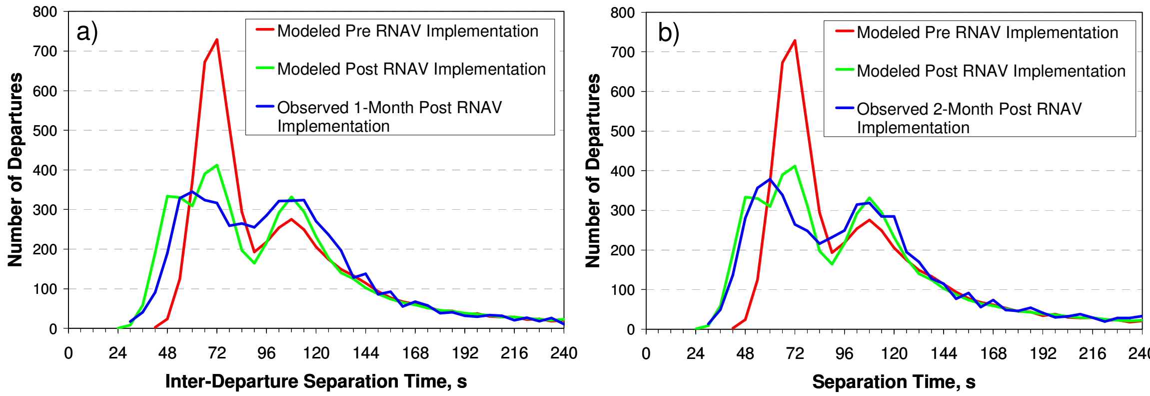


Figure 10. Comparison of inter-departure time distributions. The validated pre-implementation distribution of modeled conventional departure operations (red) is compared to post-implementation distributions of actual operations recorded 1 month (a) and 2 months (b) after implementation of RNAV departure procedures at DFW (blue). Monte Carlo model predictions are shown in green.

agreement between the performance predicted by the Monte Carlo model and evidenced in the data of actual operations suggests that benefit-enabling operational changes were largely realized within the first 2 months after implementation of the RNAV departure procedures. It is interesting to note that the some discrepancies between model performance and observed performance seem to exist at departure intervals ranging from 60 to about 75 seconds of inter-departure time. This observation is consistent with additional operational changes affecting ATC's application of *Radar Separation* standards. These additional operational changes, while identified as coinciding with RNAV procedure implementation, occurred independently and were not otherwise associated with the implementation of RNAV departure procedures at DFW.

VI. Conclusions

Incremental implementation of RNAV procedures increasingly leverages on-board navigation capabilities of advanced flight automation systems in terminal airspace surrounding DFW and other large U.S. airports. These flight automation systems are currently available on the majority of commercial and corporate aircraft and implementation of the procedures promises more efficient utilization of available runways and constrained terminal airspace. At DFW, the implementation of RNAV departure procedures on September 6, 2005 promised increased airport departure capacity, improved throughput, and reduced delay.

The research reported in this paper identified key elements of the mechanism that yields operational benefits and results in increased departure efficiency including (1) the design of the RNAV procedures featuring diverging route segments from each primary runway and (2) efficient ATC sequencing of successive departures enabling alternating use of initially diverging routes.

Potential benefits associated with the implementation of the procedures were evaluated using a model analysis approach that employs an integrated evaluation platform comprising both an agent-based Monte Carlo modeling environment and a data-driven model validation capability. The analysis results suggest potential departure capacity gains of 11 additional departure operations per hour based on DFW's current RNAV participation rate of about 84 percent. This capacity gain was found to increase to 20 additional departure operations per hour if RNAV participation was assumed to increase to full participation.

Delay model analyses were carried out to evaluate delay reduction benefits associated with the increased departure efficiency of post-implementation operations. The analysis results suggest annual delay reduction benefits to users and operators of $8.5 million for DFW. This benefit was found to increase to about $13 million annually if departure demand was assumed to increase about 13 percent above the 2005 level of departure demand. The modeling also supported estimating the cost impact of conducting mixed RNAV/non-RNAV operations. The results indicate that additional benefit of over $4 million annually could be realized if the RNAV equipment level were to increase enabling 100 percent RNAV participation. These results support cost/benefit analyses to further increase RNAV equipage of aircraft operating at DFW.

Key performance metrics of the validated Monte Carlo model were compared to performance metrics obtained from extensive post-implementation evaluations. The evaluations were found to confirm that the required operational changes that enable delay reduction benefits at DFW were largely realized within the first 2 months after implementation of the procedures.

The results of the study presented here demonstrate that incremental implementation of RNAV departure procedures can provide significant benefits to users and operators and firmly support further terminal RNAV procedure design optimization and implementation at DFW and other airports.

Disclaimer

Acknowledgments

The analysis of departure efficiency benefits of terminal RNAV operations at DFW was a collaborative effort between the FAA and MITRE. The author is indebted to Mr. Greg Juro of DFW Tower/TRACON/Metroplex HUB Traffic Management for his active involvement throughout the course of the study and thorough review of this report. The author would like to thank Mr. Jeff Williams and Mr. Bruce Tarbert of the FAA RNAV/RNP Program Office for their support of the research. The author would also like to thank Mr. Tyler Smith of MITRE/CAASD for providing procedure design information and Mr. Thang Phung for preparing the traffic files used in the simulation analysis. Many thanks to Mr. Felipe Moreno-Hines of MITRE/CAASD for providing aircraft direct operating cost estimates.

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