ANALYSIS OF POTENTIAL BENEFITS OF ARRIVAL-DEPARTURE PROCEDURES PROPOSED FOR ORD

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Abstract

On June 13, 2004 the Federal Aviation Administration (FAA) implemented a new procedure at Chicago O'Hare International Airport (ORD) that authorizes arrival-departure operations on intersecting runways 14R/27L with modified separation requirements at the runway intersection. The procedure is expected to recoup reductions in arrival and departure capacities associated with operations on these runways that resulted from discontinuing Land-And-Hold-Short Operations (LAHSO) in 2000 and reduce arrival and departure delays at ORD when the airport is operated in Plan B configuration. This configuration is used about 10 percent of the time. This paper describes the background analysis of relevant operational metrics conducted to compare and evaluate candidate procedures for their relative benefits and to help select the most promising ones. It describes the model developed to quantify and visualize the airport's operations, the methodology used to validate model performance with ARTS data, and the Monte Carlo approach taken for comparing and evaluating capacity benefits of four candidate arrival-departure procedures

Introduction

For over 30 years, Air Traffic Control (ATC) in the U.S. relied on Simultaneous Operations to Intersecting Runways (SOIR) and, more recently, on LAHSO at airports with intersecting runways as a procedural tool to increase capacity and reduce delays. LAHSO requires landing aircraft to hold short of a specified point on the arrival runway. The mechanism that enables capacity benefits of LAHSO is the removal of procedural dependencies between arrival operations conducted on one runway and arrival or departure operations on a crossing runway.

As a pilot's acceptance of a LAHSO clearance does not preclude the possible need to terminate the approach or reject the landing and to execute a missed approach procedure, aviation industry groups grew increasingly concerned about how safe separation from other traffic can be assured in such an event. This led to revisions of operational standards that significantly limit the applicability of LAHSO, mainly in terms of types of operations, participating aircraft types, and runway geometries involved [1].

Effective 14 August 2000, FAA Order 7110.118 set revised standards for conducting LAHSO. Besides establishing required minimum values of available landing distances, this order also defined specific requirements for the development of rejected landing procedures. Based on these standards and the given runway geometry, arrival-departure LAHSO was discontinued at ORD in Plan B airport configuration where arrival operations are conducted on Runway 14R and departure operations on Runway 27L. In this configuration, previously realized capacity benefits of LAHSO became unavailable, which contributed to increased delays and reduced attractiveness of Plan B as an airport operational configuration. Plan B has been in use for about 10 percent of the time in the past three years, and about 15 percent of the time in 2000 and 2001 [2]. It has been reported that it was used more frequently in prior years.

The FAA's Operational Evolution Plan (OEP) called for the development of procedures to increase efficiency of intersecting runway operations at several airports [3]. Aiming to increase arrival and departure rates through the design of new standards and procedures, the plan provided the basis for addressing safety, capacity, and other operational issues. The FAA's Office of Flight Standards, in close coordination with the Office of Air Traffic Procedures, the ORD tower and Chicago Approach Control, led these studies. Over time, several procedures were proposed and evaluated. Air Traffic Simulation, Inc. conducted the safety analysis [4]. Based on the operational scenarios defined by the results of the safety analysis, MITRE/CAASD provided the benefit evaluations. The results of the latter are reported in this paper.

On June 13, 2004 the FAA began an operational evaluation of one of the proposed procedures. The new procedure authorizes arrival-departure operations on intersecting runways 14R/27L with modified separation requirements at the runway intersection. The procedure is expected to recover some of the airfield capacity that was lost when LAHSO was discontinued in 2000, and reduce arrival and departure delays at ORD when operating in Plan B airport configuration.

Although this paper focuses on evaluating capacity benefits of proposed intersecting runway operational procedures for ORD, the methodology developed was intended to be applicable to other airports and intersecting runway configurations.

Intersecting Runway Operations

This section briefly reviews intersecting runway operations with arrivals on Runway 14R and departures on 27L at ORD under Visual Meteorological Conditions (VMC). It outlines key operational factors of operations conducted under LAHSO and after LAHSO was discontinued (subsequently referred to as post-LAHSO) and presents descriptions of the four candidate procedures that were proposed for use when ORD is operated in Plan B configuration.

LAHSO Operations at ORD

While LAHSO was in effect prior to August 14, 2000, arrival operations on Runway 14R and departure operations on Runway 27L could be conducted independently. A runway diagram of ORD is presented in Figure 1. While participating aircraft landing on Runway 14R were responsible for holding short of the runway intersection, departing aircraft could be cleared for takeoff on Runway 27L without a procedural requirement to correlate the operations, thus maximizing the capacity of the runway system.

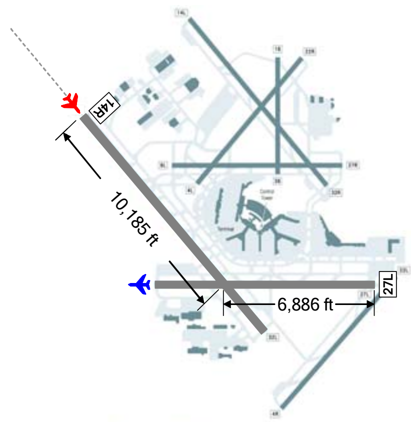

Figure 1. LAHSO Operations

Post-LAHSO Operations at ORD

Effective 14 August 2000, the use of LAHSO was discontinued at ORD for operations on Runways 14R and 27L. Departure operations could no longer be conducted independently of arrival operations. Without LAHSO, applicable ATC rules that restrict simultaneous occupancy of the 14R/27L runway system imposed significant operational constraints [5]. These constraints include (1) the requirement to make the issuance of a departure clearance contingent upon ATC's determination that the landing of the preceding arrival is assured and (2) the requirement that aircraft departing Runway 27L clear the intersection with Runway 14R before a successive arrival crosses the threshold of Runway 14R. These requirements, illustrated in Figure 2, effectively demanded close coordination between departure and arrival operations and significantly limit the amount of time available to ATC for the release of a departure. As will be seen later, the need to ensure that a departure clears the intersection prior to the time the next arrival crosses the threshold typically required that departures start to roll for takeoff at a time the next arrival sequenced for landing is located no closer than about 2 nautical miles (NM) from the threshold of Runway 14R.

Conducting departure operations consistently between arrivals necessitated the application of arrival separations in excess of 3 NM. The need for larger arrival spacing to meet the constraints associated with launching departures resulted in reductions in arrival as well as departure throughput when compared to operations previously conducted under LAHSO.

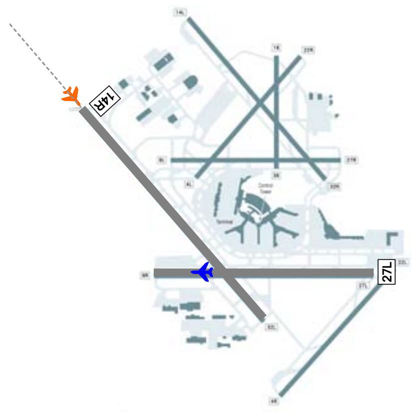

Figure 2. Post-LAHSO Operations

Proposed Intersecting Runway Operational Procedures

Four intersecting runway operational procedures were considered by the FAA's Flight Standards Division (AFS-420) based on proposals by ORD ATC Tower personnel and by representatives of the National Air Traffic Controllers Association (NATCA). The designs of all four procedures were found to provide the required level of safety [4]. The procedures define correlations between arrivals and departures and the conditions that need to exist at ORD for a departure to start to roll for takeoff.

Proposed Tower 1 Procedure

The *ORD Tower Proposed Operational Mode 1* (subsequently referred to as *Tower 1* procedure in this paper) effectively involves the definition of a *virtual threshold.* The virtual threshold is located 3,000 feet inside the landing threshold of Runway 14R. The sole purpose of the virtual threshold is to provide a procedural reference for ATC when launching departures. This conceptual definition of a virtual threshold neither impacts the threshold actually used by aircraft for landing, nor the actual touch-down zone, nor any other elements of the execution of arrival operations by aircraft. The Tower 1 procedure is illustrated in Figure 3.

The Tower 1 procedure defines a correlation between the takeoff roll of a departure on Runway 27L and the position of an aircraft approaching Runway 14R relative to the virtual threshold. This correlation stipulates that a departure is released in time to clear the intersection prior to the time the next arrival crosses the virtual threshold.

Because the virtual threshold is located 3,000 feet inside the landing threshold of Runway 14R, this procedure allows arriving aircraft to occupy the first 3,000 feet of the runway at the same time departing aircraft approach and clear the runway intersection during the takeoff roll or initial climb phase of flight. Thus, the procedure defines and effectively authorizes limited simultaneous occupancy of the runway system.

The authorization of limited simultaneous occupancy improves local ATC's flexibility of controlling departures and aides in consistently conducting departure operations between arrivals with smaller arrival spacing. Because the virtual threshold is located 3,000 feet inside the landing threshold of Runway 14R, the procedure enables departure operations between arrivals that are spaced closer by approximately ½ NM when compared to the Post-LAHSO operations.

The Tower 1 procedure described thus far establishes a correlation between a departure and a subsequent arrival. The procedure also correlates the release of a departure and a possible arrival preceding the departure. The procedure stipulates that a departure may start to roll for takeoff only after the preceding arrival has crossed the virtual threshold and that the preceding arrival is monitored by local control. The monitoring of the approach and landing is considered to serve two functions. It serves to mitigate the risk associated

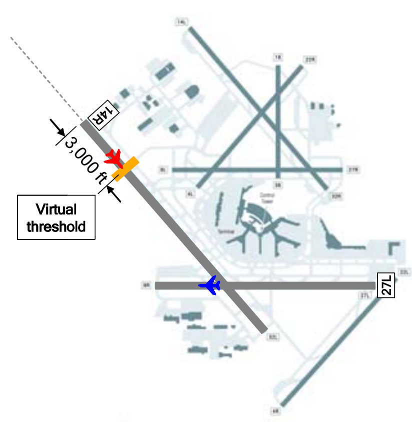

Figure 3. Proposed Tower 1 Procedure

with a potential execution of a go around by preventing a takeoff from occurring on Runway 27L in the event an approach to Runway 14R is terminated with a missed approach. Furthermore, a takeoff clearance is also withheld if no determination can be made by local control that a landing is assured by the time an arriving aircraft crosses the virtual threshold. On the other hand, if local control determines that a landing is assured, the Tower 1 procedure specifies that a departure may be released for takeoff provided the departure can clear the runway intersection prior to a subsequent arrival's crossing of the virtual threshold as described above.

Because the virtual threshold is located 3,000 feet inside the landing threshold of Runway 14R, adherence to the Tower 1 procedure effectively ensures 7185 feet of separation distance between arriving aircraft crossing the virtual threshold and departing aircraft clearing the runway intersection.

Proposed Tower 2 Procedure

The definition of the ORD Tower Proposed Operational Mode 2 procedure (subsequently referred to as *Tower 2* procedure) requires that aircraft departing Runway 27L clear the intersection with Runway 14R prior to landing aircraft reaching a point on Runway 14R that is located 5,000 feet from the intersection. Thus, adherence to the Tower 2 procedure effectively guarantees 5000 feet of separation distance between arriving aircraft landing and departing aircraft crossing the runway intersection.

The correlation between an arrival and a departure that ensures 5,000-foot of separation was determined to require that departures start to roll for takeoff on Runway 27L no later than arriving aircraft reach a distance of 1.1 NM outside the landing threshold of Runway 14R [4]. This finding enabled the definition of a Departure Decision Area (DDA) which may serve as a procedural reference for ATC when launching departures. Utilizing the definition of the DDA, the Tower 2 procedure requires that no departure starts to roll for takeoff while an arriving aircraft is within the bounds of the DDA. The DDA of the Tower 2 procedure extends from a point 1.1 NM outside to 3,000 feet inside the landing threshold as illustrated in Figure 4. On

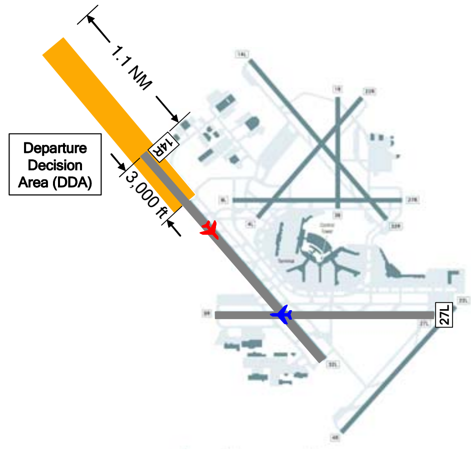

Figure 4. Proposed Tower 2 Procedure

June 13, 2004, the FAA began an operational evaluation of the Tower 2 procedure at ORD.

Proposed NATCA Procedure

The NATCA proposed procedure (subsequently referred to as *NATCA* procedure) is based on an operational scenario that was offered by NATCA representatives in 2004 [4]. The procedure defines a correlation between an arriving and a departing aircraft involving the position of the departing aircraft relative to the runway intersection at the time the arriving aircraft crosses the landing threshold.

The procedure stipulates that a departing aircraft starts to roll for takeoff at a time no later than that required to reach a pre-determined distance (Maximum Distance) from the runway intersection (on Runway 27L) before an arrival crosses the landing threshold of Runway 14R. Safety analyses were performed by AFS-420 to determine the value of the Maximum Distance that allowed meeting a target level of safety in the event an approach to Runway 14R is terminated with a missed approach [4].

The correlation the NATCA procedure establishes between an arrival and a departure was found to require that departures reach a point 1,800 feet from the threshold of Runway 27L no later than the time arriving aircraft cross the landing threshold of Runway 14R. This result enabled the definition of an Arrival Decision Area (ADA) which may serve as a procedural reference for ATC when launching departures. Thus, the NATCA procedure requires that no approaching aircraft crosses the arrival threshold while a departing aircraft is within the bounds of the ADA. The ADA extends from the threshold of Runway 27L to a point 1,800 feet from the threshold as illustrated in Figure 5.

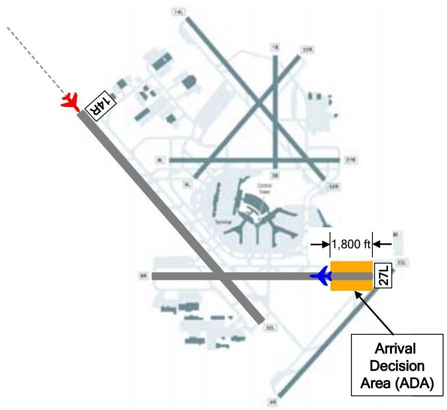

Figure 5. Proposed NATCA Procedure

Proposed Tower 1A Procedure

The ORD Tower Proposed Operational Mode 1 with Enhanced DDA procedure (subsequently referred to as *Tower 1A* procedure) is conceptually similar to the Tower 2 procedure. The definition of this procedure also involves a DDA.

The correlation the Tower 1A procedure establishes between an arrival and a departure is designed to ensure a target level of safety at the intersection in the event of a go-around [4]. This was found to require that no departure starts to roll for takeoff while an arriving aircraft is within the bounds of the DDA. The DDA of the Tower 1A procedure extends from a point 0.5 NM outside to 3,000 feet inside the landing threshold as illustrated in Figure 6.

It is noted that all candidate procedures entail varying degrees of simultaneous occupancy of the runway system and promise improvements in airfield capacity when ORD is operated in Plan B airport configuration.

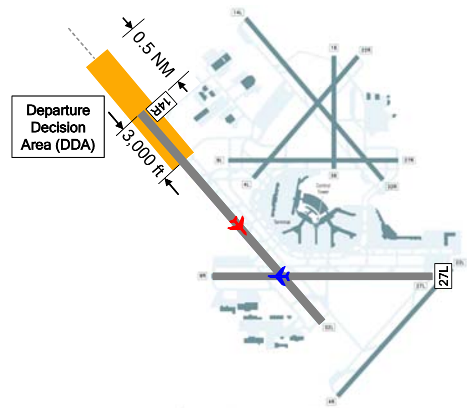

Figure 6. Proposed Tower 1A Procedure

Analysis of Post-LAHSO Operations

The approach presented here involved the development of two models. One model enabled operational analyses of intersecting runway operations as represented in radar surveillance data (subsequently referred to as SAM-OA). Output metrics of this model provided key modeling parameters for a Monte Carlo benefit analysis model (subsequently referred to as SAM-BA) of post-LAHSO and proposed procedures.

Both models share basic functionality provided by MITRE's SLX Aviation Model (SAM) including trajectory modeling as well as visualization and animation capabilities [6]. SAM is a highly flexible discrete-event aviation modeling tool that provides 4D flight trajectories. SAM enables the modeling of ATC decision-making processes under operational and procedural constraints for large numbers of flight operations [7]. Aircraft flight performance is based on Eurocontrol's Total Energy Model which, in its Base of Aircraft Data, provides performance parameters for 84 aircraft types commonly used in commercial air carrier operations [8]. The data base also supports 180 additional aircraft types by assigning each additional type to one of the 84 directly modeled types with similar performance characteristics. Key functionality of the models, their inputs and output metrics are described in this section.

Operations Analysis Model

The task of modeling LAHSO and post-LAHSO operations required the capturing of ATC procedures and local practices at a sufficient level of detail to adequately reproduce key operational metrics. For this purpose, Automated Radar Terminal System (ARTS) surveillance data provided by ORD Terminal Radar Approach Control (TRACON) were analyzed. This analysis yielded critical operational metrics and constraint information, including (1) arrival-arrival separations, (2) arrival-departure correlations, and (3) departure-departure separations.

The ARTS data analysis enabled objective, quantitative characterizations of key operational parameters for use as input to the benefit analysis model, as well as for validation of the model.

ARTS data of ORD Plan B operations, recorded on 10, 13, 17, and 19 March 2004, comprised about 50 hours and approximately 3,200 intersecting runway operations on Runways 14R and 27L. All operations represented in the data were conducted in VMC. The data provided flight track information of aircraft approaching Runway 14R up to points located a distance of about ½ NM from the threshold. For most departing flights, tracking information became first available when aircraft climbed through an altitude of about 1100 to 1300 feet above ground level (AGL) located about ¼ to 1 NM from the departure end of Runway 27L. Thus, track data of all flights, both landing and taking off, were unavailable when aircraft were close to or on a runway.

The lack of track data during landing as well as during takeoff and initial climb phases of flight precluded direct examination of any arrival-departure correlation. However, the SAM Operations Analysis model (SAM-OA) enabled such examination by modeling flight trajectories that fit and extrapolated available data, yielding estimates of portions of the flight tracks that were unavailable in the ARTS data. For arrivals, flight trajectories were extended from the last ARTS data point along the glide slope of the instrument landing system (ILS) to the runway including an estimate for the landing roll. Departing aircraft were modeled to begin takeoff roll approximately at a "position and hold" location and aligned with the centerline of Runway 27L. In this case, modeled trajectories maintained alignment until a point was reached approximately over the intersection with Runway 14R. From there, each flight proceeded directly to the first ARTS data point available for the flight. Departure times were computed so that each flight reached the coordinates of its first ARTS track point at the time associated with the recording of that data point.

The SAM-OA animation capability allowed visual examination of arrival-departure correlations as observed in the SAM-augmented ARTS data. It also provided an analysis platform for deduction and quantification of operational constraint information from reconstructed correlations.

Types of Operations. The majority of observed arrival-departure operations were found to be described by one of two cases. In the first case, the distance between two consecutive aircraft approaching Runway 14R may allow only one aircraft to depart from Runway 27L for each arrival landing. This pattern of operation is subsequently referred to as "**One-For-One**" operation. In the second case, the spacing between arrivals is generally larger and sufficient departure demand exists for two aircraft to depart between arrivals. In this second pattern of operation, subsequently referred to as "**Two-For-One**" operation, two departures are launched for each arriving aircraft.

One-For-One Operations. When conducting post-LAHSO arrival-departure operations, release of a departure is dependent upon successful completion of a preceding arrival operation. In this situation, a departure is not released until the controller can be certain that the preceding arrival will not execute a missed approach, either by visual observation or by report from the flight crew that the aircraft is on the runway and/or committed to use an assigned taxiway to clear the runway.

When landing is assured, the approaching aircraft has typically crossed the threshold and is located a certain distance down the runway. That time and associated distance clearly is dependent upon various factors including aircraft type as well as controller/flight crew style, workload, and performance and will vary from one landing to the next. However, for a given fleet mix, an average distance from the threshold is assumed to exist (inside the threshold) at which landing aircraft are typically located when departures can be cleared for takeoff. This distance may serve as metric when quantifying the operational correlation between arrivals and subsequent departures. The term **Departure Release Distance 1 (DRD1)** is used here to describe this distance that **arriving aircraft** typically are located inside the threshold when it is certain that no missed approach will be executed and when departures can be released for takeoff.

Once a departure can be released, some time is needed by the local controller to issue a takeoff clearance and by the flight crew to respond to the clearance and initiate the takeoff roll. As stated previously, that time clearly is dependent upon various factors including frequency congestion, location of the departing aircraft, and aircraft type, as well as controller/flight crew style, workload, and performance. This time will vary from one departure to the next. However, for a given fleet mix, a typical time interval is assumed to exist between issuance of a clearance and the flight crew's initiation of the takeoff roll. This time interval may serve as metric when quantifying the operational correlation between arrivals and subsequent departures. The term **Clearance Issue and Crew Response Time (CICRT)** is used here to describe this **time** interval from the moment arriving aircraft reach the DRD to the time departing aircraft typically start to roll for takeoff.

In the case of One-For-One operations, either the spacing between arrivals may be insufficient or no departure demand may exist for launch of a second departure between consecutive arrivals. Consequently, the departure is followed by another arrival. While this mode was represented predominantly in the ARTS data, Two-For-One operations were also observed when the arrival sequence provided larger arrival separations and continued departure demand existed.

Two-For-One Operations. Two-For-One operations are initially identical to One-For-One operations. In this case, however, a sufficiently large arrival spacing and continued departure demand may allow launching of two successive departures between two consecutive arrivals. The trailing departure is launched on the same departure runway (27L) and is dependent upon successful completion of the preceding departure operation. In that case, the trailing departure is not released until either applicable minimum departure separation requirements are met or the controller anticipates they will be met by the time the second departure starts to roll for takeoff.

At the time of release of the second departure, the preceding departure may be completing its takeoff roll or has become airborne. In either event, at that time the first departure is located a certain distance from the threshold of Runway 27L. Of course, that time and associated distance are determined by applicable separation minima. They are also dependent upon various factors including aircraft type as well as controller/flight crew style, workload, and performance and will vary from one departure to the next. For a given fleet mix, a typical distance may be defined as the average distance from the departure threshold of the leading departures when trailing departures can be cleared for takeoff. This distance may serve as metric when quantifying the operational correlation between arrivals and subsequent departures. The term **Departure Release Distance 2 (DRD2)** is used here to describe this distance that leading **departures** typically are located from the threshold of Runway 27L when applicable minimum departure separation requirements are met and the aircraft is cleared for takeoff.

It is important to note that the definition of a DRD2 for trailing departures generally does not imply that trailing departures start to roll for takeoff at the time leading departures reach this distance. It only describes a typical distance leading departures are required to reach before the trailing departure can be released. As described for the case of One-For-One operations, some time is needed by the local controller to then issue a takeoff clearance and by the flight crew to respond to the clearance and initiate the takeoff roll.

Arrival Demand. The distribution of aircraft separation distances between consecutive arrivals approaching Runway 14R was deduced from the ARTS data and is shown Figure 7. The distribution with a mean of 4.2 NM shows a minimum value of about 2 NM which is consistent with the fact that these operations were conducted in VMC. The distribution was used to represent the arrival demand for the subsequent model analysis.

Given the arrival separation distribution as a representation of the arrival demand as input, the SAM Benefit Analysis model (SAM-BA) served to simulate departure operations for two departure demand scenarios. In the first scenario, departure demand was limited to currently observed levels. Limiting departure demand allowed the validation of the model of post-LAHSO operations. The validated model was observed to reproduce key operational performance metrics associated with post-LAHSO operations. The capacity of post-LAHSO intersecting runway operations was then determined by removing the departure demand limitation and increasing demand to a level that exceeds the departure capacity of a single runway. Under this condition, the resulting departure throughput served as a Baseline departure capacity for comparison to the modeled capacities of proposed procedures. Key steps of the ARTS data analysis are described in the following sections.

Departure Demand. The metric used to evaluate departure demand that was present during recording of the ARTS data is the percentage of arrivals on Runway 14R that were followed by departures on Runway 27L. The results of the ARTS data analysis indicate that 77.6 percent of all arrivals were followed by one or more departures whereas in 22.4 percent of the cases no departure was observed. Instead, the arrival was followed by another arrival. When departures were observed, 63.0 percent of arrivals were seen to be followed by one departure (One-For-One), 13.3 percent by two (Two-For-One), and 1.3 percent by three departures.

Arrival-Departure Correlations. The metric used to evaluate arrival-departure correlations is the distance of arriving aircraft from the threshold of Runway 14R either on approach or on the runway when a departure starts to roll for takeoff on Runway 27L. Arrival-departure correlations observed in the ARTS data are illustrated in Figure 8. At the moment departing aircraft initiate their takeoff rolls, possible locations (measured from the threshold of Runway 14R) of arriving aircraft are seen to be distributed non-randomly along the approach to runway 14R (positive distances) or on the runway (negative distances). It shows, e.g. that a typical departure begins to roll for takeoff when a previous arrival is completing its landing roll (#1) and the next arrival (#2) is about 3 to 3.5 NM from the threshold. In no case was a departure observed to start rolling for takeoff when an arrival was inside of a 1.5 NM final. (It should be noted that the exact distances shown here depend on the extrapolation of the ARTS data by the model to the threshold, and are therefore subject to modeling errors. However, they do indicate the basic trend of the relationship between arrivals and departures required in the post-LAHSO operations). Features of the observed arrival-departure correlations were used to quantify the procedural and operational constraint parameters defined above (i.e. DRD1, DRD2, and CICRT).

Benefit Analysis Model

The SAM-BA model was structured to include an object of class "Flight" that is instantiated for each flight and that models 4D flight trajectories. SAM-BA also employed

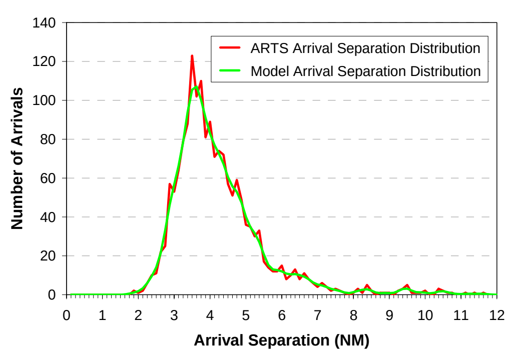

Figure 7. Arrival Separation Distributions

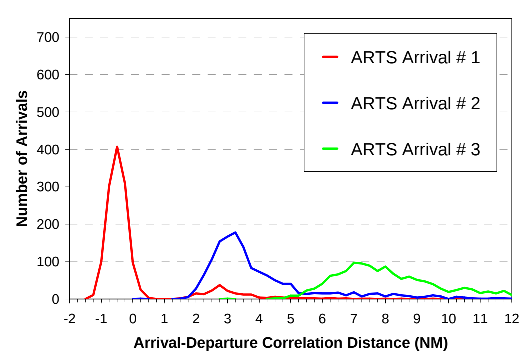

Figure 8. Observed Distance of Arriving Aircraft from the Threshold of Runway 14R when a Departure Starts to Roll for Takeoff

three object classes whose actions were designed to mirror ATC control activities under operational and procedural constraints. These controller object classes included (1) Approach Controller, (2) Ground Controller, and (3) Local Controller.

Actions of the controller objects were dependent upon stochastic variations of key trajectory modeling and operational constraint parameters in order to support Monte Carlo simulations of the procedures under investigation. The modular approach taken facilitates possible applications of the model to other operational configurations and airports. Key features and actions of the controller modules are outlined in the following sections.

Approach Control. Trajectories of aircraft approaching ORD were modeled to begin at a waypoint about 13 NM from the threshold of Runway 14R. At this point, the Approach Control object applied the required temporal separation to ensure that an approaching aircraft is spatially separated from the preceding aircraft at the time the preceding aircraft crossed the threshold. The spatial separation distance applied was randomly drawn from the distribution of separation distances that was deduced from the ARTS data.

Ground Control. Trajectories of aircraft departing ORD are modeled to begin at the arrival end of Runway 27L. After the Flight objects were instantiated, the Ground Control object applied a line-up distance to each flight. The line-up distance was randomly drawn from a distribution of distances that was assumed to represent the range that aircraft typically require to line up with the runway centerline for takeoff.

Local Control. The Local Control object ensures that required arrival-departure and departure-departure separation standards were met and decided whether or not aircraft can be launched for departure. It monitored arriving aircraft, determined the times when aircraft reached DRD1, applied CICRT times that were drawn randomly from a distribution, and decided whether departures would violate applicable rules and separation standards if they were to depart. Departures were allowed to start to roll for takeoff if they could meet all applicable separation criteria. As departure operations of proposed procedures were subject to rules that were different from the rules that govern post-LAHSO operations, the Local Control object implemented the appropriate rules that applied to the various proposed procedures under investigation.

ORD Fleet Mix. All modeled aircraft were assigned performance types that were drawn from an empirical fleet mix distribution. The fleet mix distribution was obtained from analyses of ETMS data for ORD from 22-28 February 2004. A total of 9202 arrivals were extracted for day-time operations (06:00-00:00 local time). The fleet mix was found to consist of 64 aircraft types. The distribution specified each aircraft type's relative probability to operate at ORD. The types of all modeled aircraft were randomly drawn from this distribution.

Departure Separation. As described above, post-LAHSO operations were predominantly comprised of One-For-One operations. In this case, the separation between departures on Runway 27L is largely determined by the inter-arrival times that can be achieved for approaches to Runway 14R. Generally, meeting departure separation requirements was found to be less of an operational concern in One-For-One operations. In Two-For-One operations, the need for application of required inter-departure separations represents a significant operational constraint and limits departure capacity. Key steps of the decision logic that was employed in the model to make departure go/no-go decisions are outlined in the remainder of this section.

After an arrival has reached DRD1, the model assigned the associated time plus the CICRT as the initial departure time. The model then evaluated the need for separation from a possible previous departure. If a previous departure was of Small or Large weight class, the model assumed efficient sequencing of departures which would allow application of Same Runway Separation (SRS). Otherwise, Wake Turbulence Separation was applied. Given the aircraft types involved and the resulting applicable separation distance, the model determined a second departure time that ensured the required separation from the previous departure at the time the departure become airborne. The larger of the two departure times, the initially assigned and second departure time, was then adopted as final departure time.

In a second part of the go/no-go decision evaluation process, the adopted final departure time was used to ascertain that procedural constraints would be met if the departure were to take off. In post-LAHSO operations, for example, the departure was allowed to take off provided that its intersection crossing time was earlier than or equal to the time the next arrival crossed the threshold. If the departure was found to be unable to meet this procedural constraint, the takeoff was cancelled.

Model Validation

The objective of the SAM-BA model validation process was to quantify procedural and operational constraint parameters. Constraint parameters were considered intrinsic to post-LAHSO operations if their application yielded consistency between key operational performance metrics of the SAM-BA model and similar metrics deduced from SAM-OA ARTS data analyses. Once determined for post-LAHSO operations, operational constraint parameters were retained in the modeling of proposed procedures while procedural constraints were modified according to the specifications that were provided for the various procedures.

Departure Demand

A first departure demand scenario was developed to represent an average departure demand as observed in the ARTS data and was used for validation of the model's hourly **average throughput** and arrival-departure correlations in post-LAHSO operations. In this departure demand scenario, departure demand existed following 80 percent of all arrivals. Furthermore, 48 percent of One-For-One operations provided additional departure demand for Two-For-One operations. Comparisons of the results obtained from ARTS data and from model output suggest that the reduced level of departure demand approximately represented the **average departure demand** that existed during recording of the ARTS data.

In the second departure demand scenario, the model provided the departure demand of two available departures for each landing aircraft which, given the arrival throughput discussed above, typically exceeded the departure capacity of a single runway. This departure demand scenario was employed to obtain hourly **capacity** benefit estimates when modeling both post-LAHSO operations as well as operations using the various proposed procedures.

Arrival-Departure Correlations

Arrival-departure correlations observed in the analysis of ARTS data were compared to arrival-departure correlations of similarly analyzed SAM-BA model output as illustrated in Figure 9. The model is seen to reproduce key features of the correlations observed in the ARTS data illustrated in Figure 8.

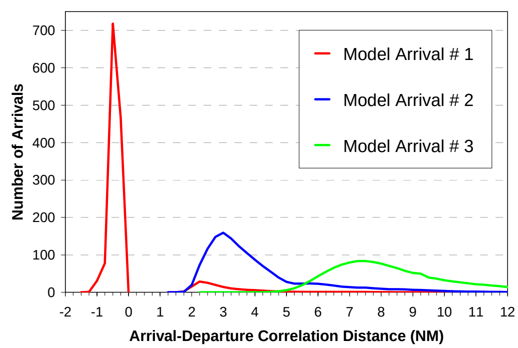

Figure 9. Modeled Distance of Arriving Aircraft from the Threshold of Runway 14R when a Departure Starts to Roll for Takeoff

Analysis of Proposed Procedures

The SAM-BA benefit analysis model presented here uses Monte Carlo techniques to estimate arrival and departure **capacities** of runway systems. The model was designed to evaluate new procedural concepts of dependently operated runways. It simulates large numbers of arrival and departure operations and employs stochastic variations in aircraft types, aircraft performances, controller, and flight crew performances.

Model Input and Execution

Model throughput and capacity results were obtained for two levels of arrival demand and two departure demand scenarios described below.

Arrival Demand and Throughput. The discrete-empirical arrival separation distribution derived from ARTS data of post-LAHSO operations was used to represent arrival demand in the model. The throughput resulting from this arrival demand scenario with an average arrival throughput of 35.8 arrivals per hour is referred to as **Today's Arrival Throughput** in the presentation of results.

A second arrival demand scenario was developed to evaluate the impact of increased arrival demand on post-LAHSO operations and proposed procedures. In this case, all arrival separation values drawn from the empirical distribution were reduced by a constant amount to lower the mean arrival separation by 0.5 NM while maintaining a similar minimum separation cutoff at 2.0 NM. The throughput resulting from this arrival demand scenario is referred to as **Increased Arrival Throughput** in the presentation of the modeling results.

Departure Demand and Capacity. The model provided departure demand that is coupled to arrival throughput as described above and exceeded the departure capacity of a single runway. The modeled departure demand supported One-For-One as well as Two-For-One operations. The definition of departure capacity used here is that of a maximum average runway departure throughput, on a long-term basis, given sustained departure demand [9].

Model Execution. Post-LAHSO operations and each of the proposed procedures were modeled by performing multiple replicates of Monte Carlo simulation runs. Each simulation run modeled 500 arrivals approaching and landing on Runway 14R and a similar number of departures depending on the modeled procedure. Thus, each simulation run approximately represented one day of intersecting runway operations in Plan B airport configuration. Monte Carlo runs were replicated 1,000 times, such that each modeled scenario was composed of 500,000 arrivals resulting in approximately one million intersecting runway operations. The modeling results presented in this section are based on a total of 20.6 million simulated operations.

Modeling Results

While the modeling results suggest potential benefits for all proposed procedures, they were found to vary significantly depending upon the procedure and the separation distribution of arriving aircraft. Benefit results for the 14R-27L runway system are summarized in Table 1.

Using **today's arrival throughput** on Runway 14R averaging 35.8 arrival operations per hour and adding the modeled departure capacity of Runway 27L, the resulting performance of the 14R-27L runway system was found to range from 76 to 90 operations per hour for post-LAHSO

Table 1. Modeled Arrival-Departure Operations on Runways 14R-27L and Hourly Benefits

Procedure	Arrival-Departure Operations Per Hour (Runways 14R and 27L)			
	Today's Arrival Throughput		Increased Arrival Throughput*	
	Operations	Benefit	Operations	Benefit
Post-LAHSO	76.0	–	77.7	+2 (2 %)
Tower 1	80.7	+5 (6 %)	84.4	+8 (11 %)
Tower 2	82.9	+7 (9 %)	87.2	+12 (15 %)
NATCA	84.4	+8 (11 %)	88.6	+13 (17 %)
Tower 1A	89.9	+14 (18 %)	93.9	+18 (24 %)

* Mean arrival spacing reduced by 0.5 NM resulting in 4 additional arrivals per hour

operations and the various proposed procedures. Benefits were seen to range from 5 to 14 additional departure operations per hour assuming no changes in the arrival spacing of aircraft on approach to Runway 14R without adversely affecting the ability to conduct departure operations on Runway 27L.

The proposed procedures were found to offer the possibility of reducing inter-arrival spacing and thus increasing arrival throughput on Runway 14R without adversely affecting departure operations on Runway 27L. Using **increased arrival throughput** on Runway 14R averaging 39.6 arrival operations per hour and adding the modeled departure capacity of Runway 27L in intersecting runway operations, the resulting performance of the 14R-27L runway system was found to range from 78 to 94 operations per hour for post-LAHSO operations and the various proposed procedures. In this case, benefits were found to range from 8 to 18 additional operations per hour (arrivals and departures).

Conservative assumptions were made in this analysis. Depending on the operational implementation, benefits in excess of these estimates may accrue.

Based on ORD tower operational considerations, the Tower 2 procedure was selected for an operational evaluation. This evaluation began on June 13, 2004.

Summary

Potential airfield capacity benefits of four candidate procedures were evaluated for intersecting runway operations at ORD on Runways 14R and 27L. In this operation, the airfield's runway layout in conjunction with ATC simultaneous occupancy rules applicable to the two crossing runways significantly constrains departure operations on intersecting Runway 27L.

In order to improve departure performance, operational practice established after August 2000 (i.e. after LAHSO was discontinued) routinely called for delivery of arriving aircraft at larger arrival spacing. This practice limited arrival throughput for gains in departure throughput and nearly balanced departure throughput at a level of reduced arrival throughput.

All proposed procedures were found to effectively modify separation requirements at the runway intersection and authorize limited simultaneous occupancy of the 14R-27L runway system. Monte Carlo capacity modeling of the departure procedures showed that all procedures support both increases in arrival throughput on Runway 14R and simultaneous improvements in the departure capacity of Runway 27L. When arrival throughput was increased by 4 operations per hour, by decreasing the inter-arrival spacing, the performance of the 14R-27L runway system was found to improve by 8 to 18 operations per hour depending upon the procedure.

For one of the procedures, the Tower 2 procedure, modeling results indicated potential airfield capacity benefits of 7 to 12 additional operations per hour. This procedure was selected for an operational evaluation, based on local operational considerations. This evaluation began on June 13, 2004.

The implementation of new intersecting runway procedures promises to maximize the use of existing runways and to expand their use in crossing runway operations. The modeling results suggest that the procedures may allow regaining at least some of the capacity losses experienced at ORD in 2000 when LAHSO operations were discontinued.

The modeling results also suggest that it may be possible to develop criteria for a more general application to intersecting runway operations for improving their arrival/departure capacities. It is recommended that such a general analysis be pursued.

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