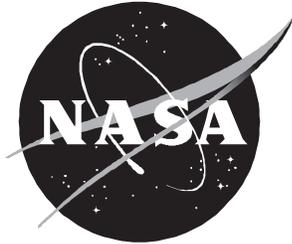


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The Aviation System Analysis Capability Airport Capacity and Delay Models

*David A. Lee, Caroline Nelson, and Gerald Shapiro
Logistics Management Institute, McLean, Virginia*

April 1998

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The ASAC Airport Capacity and Delay Models

FEBRUARY 1997

EXECUTIVE SUMMARY

Current forecasts of growth in air traffic demand indicate that the existing capacity at many of the busiest airports will be inadequate to avoid exponentially increasing delays. NASA is investigating new technologies and operational tools that will reduce some of the current constraints on airport capacities.

To meet its objective of assisting U.S. industry with the technological challenges of the future, NASA must identify research areas that have the greatest potential for improving the operation of the air transportation system. Therefore, NASA seeks to develop the ability to evaluate the potential impact of various advanced technologies. By thoroughly understanding the economic impact of advanced aviation technologies, and by evaluating how these new technologies would be used within the integrated aviation system, NASA aims to balance its aeronautical research program and help speed the introduction of high-leverage technologies. To accomplish this goal, NASA is building an Aviation System Analysis Capability (ASAC).

The ASAC is envisioned primarily as a process for understanding and evaluating the impact of advanced aviation technologies on the U.S. economy. ASAC consists of a diverse collection of models, databases, analysts, and other individuals from the public and private sectors brought together to work on issues of common interest to organizations within the aviation community. ASAC also will be a resource available to those same organizations to perform analyses; provide information; and assist scientists, engineers, analysts, and program managers in their daily work.

The ASAC Airport Capacity Model and the ASAC Airport Delay Model support analyses of technologies addressing airport capacity. There are two primary constraints on airport capacity that NASA technologies address. The first is arrival runway occupancy time (AROT), the time from when an arriving aircraft crosses the end of the runway until it turns off the runway. For safety reasons, only one aircraft may occupy a runway at any time. Reducing AROT may allow a quicker tempo on the runway, thus increasing the airport's capacity. Reducing the uncertainty in AROT may allow air traffic controllers to shorten the spacing between successive arrivals without compromising safety, also increasing airport capacity.

The amount of time an aircraft requires on a runway and its standard deviation (uncertainty) are input values to the ASAC Airport Capacity Model. The user can compare airport capacity with typical AROT values (which are airport specific) versus capacity with reduced AROT values anticipated as a result of a new technology.

The second major factor affecting airport capacity is the separation that must be maintained between any two airborne craft in the terminal environment. The current separation standards are determined on the basis of safety concerns. Some NASA initiatives provide technology that may enable aircraft to operate in closer proximity without compromising safety.

Separation requirements are also ASAC Airport Capacity Model inputs. The user may set the separation criteria (which are weather dependent) to those appropriate to a new technology and examine the resulting capacity impact.

Other Federal Aviation Administration operational rules may become obsolete if new technologies are developed. The user can direct the ASAC Airport Capacity Model to either take into account or disregard these rules, as appropriate to the technology under examination.

The ASAC Airport Delay Model allows the user to estimate the minutes of arrival delay for an airport, given its (weather dependent) capacity. Historical weather observations and demand patterns are provided by ASAC as inputs to the delay model. The ASAC economic models can translate a reduction in delay minutes into benefit dollars.

The ASAC models have been developed to account for the peculiarities of each modeled airport, determined on the basis of interviews with air traffic controllers responsible for operations at the airport. The results of each airport model, using current AROTs and separations, have been reviewed by these air traffic controllers, and their concurrence with the models' results has been obtained.

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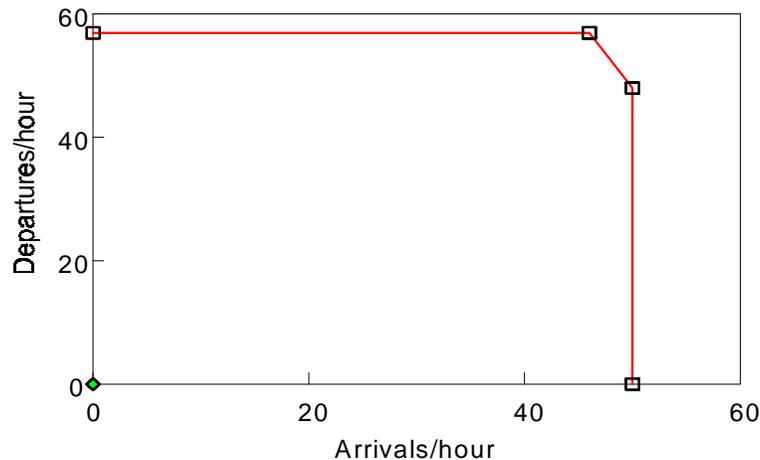
Chapter 1

The ASAC Airport Capacity Model

NASA's Aviation System Analysis Capability (ASAC) Airport Capacity Model estimates the capacity of an airport as a function of weather, Federal Aviation Administration (FAA) procedures, traffic characteristics, and the level of technology available. Airport capacity is presented as a Pareto frontier of arrivals per hour versus departures per hour. This frontier is the set of points at which arrival rate and departure rate cannot be simultaneously increased.

Figure 1-1 gives an example capacity curve. The figure indicates that, when departures are given priority, Newark International Airport can accommodate up to 57 departures per hour. The airport can integrate up to 46 arrivals per hour into the departure stream while maintaining that departure rate. The airport can increase the arrival rate to more than 46 per hour only by decreasing the departure rate. By decreasing the departure rate, the airport can increase the maximum arrival rate to up to 50 per hour. (An airport capacity curve is not necessarily made up of straight-line segments as in the example.)

*Figure 1-1. Example of Airport Capacity:
Newark International Airport*



Actual airport capacity varies with, among other factors, ceiling, visibility, wind speed, and wind direction, so that a complete specification of airport capacity is a family of curves like that in Figure 1-1. The ASAC Airport Capacity Model presents a capacity curve for each of five weather conditions: visual approaches (VMC1); radar approaches with visual completion (VMC2) and three categories of instrument approaches—IMC1, IMC2, and IMC3. The airport capacities may

vary in the different IMC cases, as some runways may not be available as the weather deteriorates. The ceiling and visibility criteria that define weather conditions and runway availability were obtained from air traffic controllers at each modeled airport and from published information about these airports.

The capacity models present the weather-dependent set of frontiers for each *airport configuration*. An airport configuration is the specification of geometry and strategy; that is, which runways are being used and how they are being used. For example, a typical configuration at Detroit Metropolitan Wayne County Airport (DTW) is to use runways 21L, 21C, and 21R (geometry), with 21L used for arrivals only, 21C for departures only, and 21R used for departures and arrivals in the proportion needed to best satisfy demand (strategy).

Although each airport model has unique configuration logic, all the airports use the same analytical tools to translate technology, traffic characteristics, and operational rules into runway capacity. This suite of tools comprises the Runway Capacity Module, discussed in the next section.

THE RUNWAY CAPACITY MODULE

The Runway Capacity Module analyzes runway capacity, incorporating parameters related to the separation requirements for aircraft, runway occupancy times, controller information, and operational rules that advanced technologies can affect. The Runway Capacity Module takes a controller-based view of airport operations. The limitations on the quality of information accessible to the controller—such as aircraft position and speed—directly affect the spacing required for safe operation of aircraft streams.

Table 1-1 lists the key parameters used in the ASAC Runway Capacity Module. This module determines controller-applied separation of aircraft at the beginning of the common approach path (the last point at which instructions may be issued to the aircraft) on the basis of aircraft performance parameters, required separation, and the requirement that two arriving aircraft not occupy the runway at the same time. Uncertainties about aircraft position and speed require the controller to apply separations greater than the minimum required at the beginning of the common path, to achieve the required separation from the outer marker to the runway threshold with a specified level of statistical confidence. Uncertainty about runway occupancy time similarly requires the controller to apply greater separation to ensure that two aircraft do not occupy the runway at the same time.

To model a particular technology, the user may toggle (on or off) or set parameters in specific operational rules affecting capacity, as appropriate. One such rule is the required departure hold time after a “heavy” jet departure. Current FAA procedures classify an aircraft as heavy if its gross takeoff weight can exceed 255,000 pounds. Such aircraft generate strong wingtip vortexes. The current rule requires that, after a heavy jet departure, the next departure on the same or parallel

runway within 2,500 feet cannot occur for 2 minutes. A related rule specifies a 3-minute wait before allowing an arriving or departing aircraft to fly through the flight path of a heavy jet at a runway intersection. The ASAC user may leave the wake vortex rules as is, adjust either or both hold times, or toggle the rules off.

Table 1-1. Capacity Model Parameters

Symbol	Definition
p_i	Fraction of aircraft in class i
S_{ij}	Miles-in-trail minimum, class i behind j
V_i	Approach speed
D	Common path length
R_{Ari}	Arrival ROT on runway r
σ_{RAri}	Standard deviation of arrival ROT on runway r
R_{Di}	Departure ROT
σ_{RDi}	Standard deviation of departure ROT
D_{Dr}	Distance to turn on departure on runway r
V_{Di}	Departure speed
σ_{VDi}	Standard deviation of departure speed
σ_{xi}	Standard deviation of position uncertainty
σ_{Vi}	Standard deviation of approach speed
σ_w	Standard deviation of wind speed
c	Mean communications delay
σ_c	Standard deviation of communications delay

Note: Subscripts indicate variation with aircraft class. ROT means runway occupancy time.

Another rule requires that, if an arriving flight cannot make visual contact with the runway within 2 miles of the threshold, no departure can be released from that runway from the time the arriving flight is 2 miles out until it lands. This restriction also applies to a departure on a parallel runway within 2,500 feet. Advanced technologies may enable a departure release with confidence in this situation; if so, the user may either toggle this rule off or adjust the release distance to a value less than 2 miles.

From the controller-applied separation, the module determines the time between arrivals of different aircraft classes. It computes a weighted average of these inter-arrival times to estimate the runway capacity. The module considers different operating strategies for a single runway (maximize arrival rate, maximize departure rate, balance arrival and departure rates) to generate a Pareto frontier of single runway capacity.

Appendix A, the *ASAC Airport Capacity Model and Delay Models Users Guide*, includes sample input and output views. Appendix B details the derivation of the

Runway Capacity Module and how the inputs are translated into controller-applied separations.

MULTIPLE RUNWAY MODULES

In some cases, the airport geometry is such that different runways can be operated independently in certain weather; in these cases, the capacity of the configuration can be determined from the capacities of the individual runways in that configuration. The technique for combining a set of runway Pareto frontiers to arrive at the configuration capacity curve is described in Appendix C.

In other cases, operational interactions among different runways reduce the capacity of the runways. In some cases this is modeled at the airport model level, using site-specific rules for determining the capacity of a configuration from the individual runway capacities. These site-specific rules are based on consultation with the air traffic controllers who work at the airport. Details are included in the descriptions of individual airport models; for example, see Appendix D for the description of the DTW capacity model.

Other cases of runway interaction are common enough to warrant additional analytical modules to compute the runway group capacity directly from the parameters that determine controller and aircraft behavior, as in the Runway Capacity Module. Two such modules are described in the following subsections.

Departures on Closely Spaced, Parallel Runways

The operational rules for parallel runways depend upon the centerline separation of the runways. If the runways are separated by no more than 2,500 feet (but at least 700 feet), a particular set of operational rules are stipulated by the FAA. Following convention, parallel runways separated by no more than 2,500 feet are referred to in this document as “closely spaced, parallel runways.”

One restriction on closely spaced, parallel runways applies if both runways are being used to conduct departure operations. After a heavy jet departs, no departures are permitted from either runway for 2 minutes. The user can instruct the ASAC Airport Capacity Model to take this rule into account, disregard it, or use the rule with a delay value of less than 2 minutes, as appropriate to the technology under consideration.

Further restrictions on closely spaced, parallel runways are in place when one runway is used for departures, the other used for arrivals, and weather conditions do not allow visual contact by arrivals when they are 2 miles from the threshold. In this case departures must be held whenever an arriving aircraft is within 2 miles of the threshold. A special module is not needed for this case because the pair can be modeled as a single runway, with departures experiencing no runway occupancy time for arrivals.

A final set of restrictions on closely spaced, parallel runways occur when both runways are used for departures and departing aircraft are not visible 1 mile out. In this case separation requirements exist both for aircraft departing the same runway and for aircraft departing the other runway. This is referred to as “staggered departures.” The modeling technique used to derive capacity for this situation is described in Appendix E.

Staggered Arrivals

Under certain conditions, FAA procedures permit independent arrivals on parallel runways with centerlines separated by at least some minimum distance (currently 700 feet). Such operations are referred to as “simultaneous.” As ceiling or visibility degrades, safety considerations may require that more restrictive operational rules be enforced, which results in spacing requirements between the arrivals on the parallel runways. The modeling technique used to derive capacity in this case is essentially the same as the one used for staggered departures, and it is described in Appendix E.

PARAMETERS AND DATA SOURCES

In the ASAC Airport Capacity Model, the aircraft are designated as being in a particular *aircraft class*. Aircraft in the same class have the same average values for approach speed, departure speed, arrival runway occupancy time, and departure runway occupancy time. The standard deviations of these quantities account for both randomness in performance and variations from the mean within the class.

Each aircraft class is also identified as being heavy or not. The wake vortex hold-time rules (see description in The Runway Capacity Module section) apply to aircraft departing after, or flying through the flight path of, a member of the heavy classes.

For some airports runway usage is constrained to aircraft with a noise profile below some threshold. For these airport models, each class must be identified as noise track restricted or not.

The other data that depends on aircraft class are the *separation matrixes*. Each separation matrix gives the required terminal area separation (in nautical miles) for each class combination of leader and follower. The user must specify three such matrixes: one for visual approaches (VMC1), one for radar approaches with visual completion (VMC2), and one for instrument approaches (IMC).

The user completes the traffic specification by entering, for each aircraft class, the fraction of total traffic that the class contributes.

The generality of the aircraft descriptions permits a wide variety of analyses to be performed. The user may define aircraft classes to suit his or her needs.

Airport-specific data, such as *common path length* and *distance-to-turn on departure*, are provided by ASAC as defaults. The default values are based on discussions with air traffic controllers at each airport.

Communications delay is also provided as a default. Communication delay models the time from when a departure clearance is issued to when takeoff roll begins.

Another value provided as a default is the *standard deviation of wind speed*. This standard deviation is based on typical variations within an hour, or between different strata. The long-run variation in wind speed is not appropriate here, as the ASAC Airport Delay Model receives the actual surface-wind data for each hour from a weather database.

A final user input to the ASAC Airport Capacity Model applies only for those cases where staggered departures or staggered arrivals may be used. (See Multiple Runway Module for a description of these modules.) The capacity for these runways is estimated by bounding the capacity from below and above. The user may set an integer computational parameter that controls the bounding process. The larger the value of the parameter, the more effort is put into making the bounds close, at the expense of additional computational time. ASAC provides a default value that gives a good tradeoff between accuracy and time. The ASAC output enables users to see the value of the upper and lower bounds, so as to make determinations about increasing or decreasing the parameter value. A full description of the technique is contained in Appendix E.

The ASAC user may modify the default values described in this section.

LIMITATIONS OF RUNWAY MODULES

The ASAC Runway Capacity Module assumes that traffic appears in a random fashion. In fact, the controllers have some flexibility in sequencing arrivals to achieve desirable ordering (i.e., a heavy jet behind a small jet, rather than the reverse). The controllers do not have unlimited flexibility in this regard, however, so modeling this aspect of air traffic control is best addressed at an airport-specific level. Not accounting for arrival or departure sequencing will result in slightly pessimistic estimates of capacity.

LIMITATIONS OF AIRPORT CAPACITY MODELS

Airports and weather are highly complex systems; a model with high fidelity would require both extensive development effort and long run times. Such models

already exist; however, to provide rapid indication of the likely effects of advanced technologies, the ASAC model developers consciously constructed the airport models to reflect the predominant features of the arrival and departure environment, while ignoring those rare situations (runway closures due to maintenance, for example) that will not have a significant long-term impact.

It is not uncommon for airport capacity to be limited by ground traffic congestion near the gates. The ASAC models do not include a surface-movement component, other than reductions in capacity needed for arrivals to taxi across active runways in some configurations. The models needed to analyze delays due to gate congestion may find the unimpeded capacity results of the ASAC Airport Capacity model useful as input.

Chapter 2

The ASAC Airport Delay Model

The ASAC Airport Delay Model focuses on arrival delays. These delays account for the bulk of the users' costs. The delay model uses the results of the ASAC Airport Capacity Model as an input. If users have an alternative means of computing capacity, they can present a file in the proper format to the ASAC Airport Delay Model without first running the ASAC Airport Capacity Model. The required format is airport specific and is described in the documentation for each airport model. See Appendix A for an example.

Computing arrival delays requires two relatively independent components. The first component is airport specific: determining the specific arrival or departure capacity curve point of each configuration, given the current weather data (precipitation, wind direction, wind speed, ceiling, and visibility) and demand, and selecting the best configuration. The second component is the same for all airports: using the selected configuration capacity and demand data to arrive at delay estimates.

In the ASAC Airport Delay Model, an aircraft is considered delayed if it is not able to land as soon as possible. The ASAC Airport Delay Model Queuing Module computes a statistical estimate of delay due to congestion given the arrival demand and airport capacity. Even in those cases where demand is less than capacity, some delay will be reported. This is because the statistical estimates account for the random nature of queuing systems, in which arrivals in close temporal proximity will generate a delay, even though the long-run average capacity of the system exceeds demand. Of course, the more that capacity exceeds demand, the smaller the estimate of delay. In fact, because of the hub-and-spoke scheduling practices common among the major airlines, arrivals tend to be bunched even more tightly than randomness alone would suggest. As such, the delay estimates of the ASAC system are optimistic. This optimism should not impair the ASAC Airport Delay model's ability to compare capacity enhancements because the nature of the error is consistent in all scenarios.

In the absence of congestion, some flights will arrive sooner than scheduled. The ASAC Airport Delay Model does not reduce the delay metric to account for early arrivals; it only tallies the minutes later than expected.

MODEL RESULTS VERSUS REPORTED PERFORMANCE METRICS

Both the FAA and the airlines keep records of delays due to congestion in the air traffic system. Neither data source is likely to agree with the arrival delays reported by the ASAC Airport Delay Model because of the methods used to record delays.

The ASAC Airport Delay Model accounts for delay in arrival time due to congestion. This delay may be incurred by speed reductions or vectors assigned by air traffic controllers, as well as by the less common occurrence of airborne holding.

The FAA's delay reporting system, OPSNET, only assigns delay if airborne holding is used by controllers, and then only if the time spent holding exceeds a minimum threshold (currently 15 minutes). Additional flight time caused by speed reductions or vectoring are neither recorded by controllers nor reported in OPSNET.

The airlines' delay information, as recorded in databases such as the Airline Service Quality Performance (ASQP), is based on scheduled segment length as the nominal flight duration. To maintain on-time performance, and to make sure that connecting passengers have enough time to transfer at the destination, the scheduled segment lengths are computed by the airlines to account for anticipated delays above the unimpeded flight time. Thus the ASQP delay information only reflects delays beyond that anticipated, as contrasted with the ASAC delay metric, which does not anticipate any delay.

Although the delay metrics computed by the ASAC system are not directly comparable to existing reported delay data, for purposes of evaluating the effects on system capacity, the ASAC metric is preferable. It is not biased for existing congestion, nor does it ignore delays because of their small duration or the means by which they were incurred.

CONFIGURATION SELECTION

The ASAC Airport Delay Model takes as inputs hourly weather data. These data consist of precipitation, wind speed, wind direction, ceiling, and visibility. The model uses airport-specific rules to determine which runways can be used, given the weather of that hour. For a configuration to be usable, all of its runways must be usable. The weather data also determine the capacity curve that describes each configuration. The model uses the hourly demand to determine the operating point

on each configuration's capacity curve that has the same ratio of arrivals to departures as the demand. The configuration selected as the one that would be operated is the one with the greatest total capacity. Output to the queuing module is the demand and capacity for that hour.

ARRIVAL DELAY QUEUING MODULE

The sporadic nature of air traffic demand, combined with the fluctuations in airport capacity due to weather, results in a system that only reaches a scenario of constant arrival rate and constant acceptance rate (steady state in queuing terms) during those uninteresting early-morning hours when no one is flying. During the periods of interest, the conventional closed form queuing formulas, which rely on steady state assumptions, are of little value in estimating delays. ASAC requires a more dynamic model.

The ASAC queuing module is an implementation of a published algorithm.¹ It uses a simplifying approximation to generate the time-dependent mean number in the system for a nonstationary queuing system, such as an airport. Empirical results indicate that the method is sound.

PARAMETERS AND DATA SOURCES

The hourly demand data for each airport are based on the 1993 schedule of aircraft operations published in the *Official Airline Guide* (OAG). For most large U.S. airports, which are the airports modeled in ASAC, the amount of traffic due to nonscheduled aircraft (military flights and general aviation) is an insignificant proportion of the total traffic mix. In those cases where discussions with air traffic controllers indicate that nonscheduled traffic may be significant, the OAG data has been modified to account for that traffic.

The ASAC Airport Delay Model uses the FAA's Terminal Area Forecast (TAF) data to estimate the growth in air traffic demand from 1993 to each following year (up to 2015). The user may choose a TAF traffic-inflation factor to increase the demand by some multiple of the 1993 baseline. The user may also input a traffic-inflation factor that is independent of the TAF.

The weather data the model provides to the user are from actual observations at the airport in question. An entire year of historical data is provided for each airport. The year is selected to be typical for that airport, in that the number of hours in each meteorological condition is roughly the same as the long-run average number of hours per year in each meteorological condition. The user may choose any beginning and ending day within the range of weather data available.

¹ Michael H. Rothkopf and Shmuel S. Oren, "A Closure Approximation for the Nonstationary M/M/s Queue," *Management Science*, 25:6, June 1979, pp. 522-534.

LIMITATIONS OF AIRPORT DELAY MODELS

The ASAC Airport Delay Model does not account for delays attributable to airline scheduling practices that compact demand into small portions of each hour. As this assumption is the same in all scenarios, it should not affect comparative analysis.

The model also does not account for the flight cancellations and schedule disruptions that occur in severe weather. The ASAC Airport Delay Model assumes that airlines intend all their arriving aircraft to arrive during their scheduled hours. As airport capacities are generally greatly reduced in such weather conditions, the ASAC Airport Delay Model will indicate a great deal of delay. In practice, this delay may have occurred on the ground and not in the air; however, as the occurrence of such weather is relatively rare, the lack of fidelity in this regard should not appreciably affect the usefulness of the results.

Chapter 3

Conclusions

The ASAC Airport Capacity Model uses a set of parameters describing the rules of the air traffic system and the performance characteristics of the aircraft using it to compute runway capacities. The model combines runway capacities to generate capacity curves, which describe the tradeoff space between arrivals and departures, for each operational configuration at the airport and for each category of weather at the airport that affects operational rules.

The generality of the parameters allows the user to model the capacity impacts of changes to the basic characteristics of the system. The air traffic controllers working at each modeled airport evaluated the baseline cases of the model, using current operational parameters, and concurred on the model's accuracy for their airport.

The ASAC Airport Delay Model uses the results of the ASAC Airport Capacity Model, together with actual weather observations and demand patterns, to determine the airport configuration and its capacity for each hour of the sample days selected. The resulting demand and capacity values are delivered to a queuing module, which computes the expected delay at the airport under those conditions.

The ASAC modelers designed the capacity and delay models to give rapid results while maintaining sufficient complexity to account for the major features affecting the air traffic system. The resulting system is a powerful tool for analysts to use for quick evaluation of the delay reductions at existing airports that would result from changes in the system parameters. In conjunction with the ASAC economic models, the ASAC airport models will provide a user-oriented system that facilitates benefit calculations of advanced air traffic tools and technologies.

References

- [1] Michael H. Rothkopf and Shmuel S. Oren, "A Closure Approximation for the Nonstationary M/M/s Queue," *Management Science*, 25:6, June 1979, pp. 522–534.

Appendix A

ASAC Airport Capacity and Delay Model

Users Guide

AIRPORT CAPACITY MODEL

The ASAC Airport Capacity Model is located in the “Model Wizard” and may be accessed at the following address:

<http://www.asac.lmi.org/access/model-wizard/>

It is also accessible through the ASAC home page by making the following choices, in sequence:

- ◆ select “Quick Response System (QRS)”
- ◆ select “Enter”
- ◆ select “Model Server”
- ◆ select “Model Wizard”

However the Model Wizard is accessed, the ASAC Airport Capacity Model is accessed by:

- ◆ selecting “ASAC Airport Capacity Model” from the main dialog box
- ◆ clicking on “CONTINUE”

To perform an integrated capacity-delay analysis, using the ASAC Executive Assistant is the preferred method of access. From the ASAC home page, select:

- ◆ “Executive Assistant”
- ◆ “Enter”
- ◆ “Air Traffic Management Analysis”
- ◆ “CONTINUE”

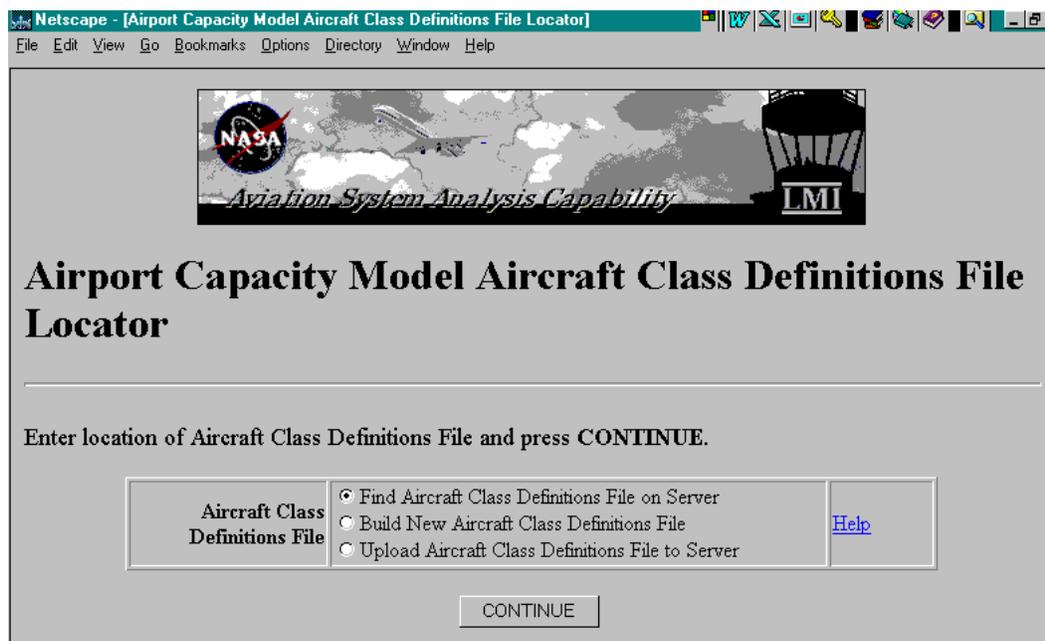
When access to the capacity model is through the Executive Assistant, the session name and capacity model output will automatically be transferred to the ASAC Airport Delay Model.

Upon entering the capacity model, a brief description of the model appears, including a list of its four user input components: (1) aircraft class definitions; (2) aircraft separation matrices; (3) operating environment; and (4) runway.

On this screen, the user is prompted for a session name. The session name will be used to identify all data and output files created during this session. A default name is provided. After entering a session name (or accepting the default), clicking on “CONTINUE” will take the user to the next screen and through the user input components in the order they are listed above, to allow the user to customize the capacity model.

Aircraft Class Definitions Component

The Airport Capacity Model Aircraft Class Definitions File Locator (Screen 1) is the first screen to be displayed after selecting a session name. It offers the user the following three choices for loading information into the capacity model:



Screen 1

- ◆ “Find Aircraft Class Definitions File on Server” enables the user to select a file that is available on the ASAC system. This file may be used as is, or it may be edited and saved. After selecting “Find Aircraft Class Definitions File on Server” and clicking on “CONTINUE”, a list of available files is displayed. Select a file from the list box, then click on “CONTINUE”. The user may next click on “VIEW/EDIT FILE” or “CONTINUE”. If “VIEW/EDIT FILE” is selected, a screen with editable data fields, similar to Screen 2, will be displayed. Move between editable fields by using the [Tab] key on the keyboard or by clicking on the desired field. At this point the user may make changes to the information or continue to view all the different screens of information by

selecting "VIEW/EDIT NEXT AIRCRAFT CLASS" until all the related screens have been viewed and/or changed as needed.

Enter or edit Aircraft Class Definition values. Press **RESET** to restore original values.

Aircraft Class Definition

Class 1 of 3

Name: Heavy Jet: Yes No

Percent of total traffic mix: % (0 - 100)

Positional uncertainty to ATC: nautical miles

Category	Value	Standard Deviation
Approach Speed	<input type="text"/> knots	<input type="text"/> knots
IMC Arrival Runway Occupancy Time	<input type="text"/> minutes	<input type="text"/> minutes
VMC Arrival Runway Occupancy Time	<input type="text"/> minutes	<input type="text"/> minutes
Departure Runway Occupancy Time	<input type="text"/> minutes	<input type="text"/> minutes
Departure Speed	<input type="text"/> knots	<input type="text"/> knots

Screen 2

If at any point the user decides that changes are unnecessary, even though some have been made, clicking on the "RESET" button will reproduce the original information on that screen.

The browser's Back button can be used to return to editing a previous screen. "VIEW/EDIT NEXT AIRCRAFT CLASS" must be clicked to save new changes.

At the end of the editing process, select "FINISHED VIEWING/EDITING FILE". The next screen allows the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on "SAVE CHANGES" for any changes made. The file will be saved with the given name in the user's ASAC directory. Alternatively, the user may click on "CONTINUE" if there are no changes.

- ◆ "Build New Aircraft Class Definitions File" enables the user to develop a file with customized information, (Screen 2). Once all the different classes with pertinent information have been created, click on "FINISHED BUILDING FILE". The next screen allows the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on "SAVE FILE". The file will be saved with the given name in the user's ASAC directory.

There is a limit of seven classes that may be defined when building a model online. To create a model with more than seven classes, the "Upload Aircraft Definitions File to Server" option must be selected.

- ◆ "Upload Aircraft Definitions File to Server" enables the user to use a file from their own computer. Up to 27 classes may be defined in an uploaded file. Follow the instructions that are listed on the screen for this process.

Uploaded input file format. The uploaded aircraft class definitions file must begin with an integer giving the number of classes to be defined. Each class definition is then given on a separate line, with fields separated by the tab character. The user may add comment lines to the uploaded file by inserting the character # in the first column of the line; any such lines are ignored by ASAC.

The fields, in order, are:

- ◆ class name
- ◆ heavy jet flag (1 if heavy, 0 if not)
- ◆ approach speed
- ◆ standard deviation of approach speed
- ◆ IMC arrival runway occupancy time
- ◆ standard deviation of IMC arrival runway occupancy time

- ◆ VMC arrival runway occupancy time
- ◆ standard deviation of VMC arrival runway occupancy time
- ◆ departure runway occupancy time
- ◆ standard deviation of departure runway occupancy time
- ◆ departure speed
- ◆ standard deviation of departure speed
- ◆ percentage of this class in airport traffic
- ◆ positional uncertainty to ATC.

The *class name* may be any name the user selects.

Heavy jet flag indicates whether wake vortex hold rules apply for departures after this aircraft class.

Approach speed is the average speed over the length of the common path. *Departure speed* is the average speed over the distance until which departures may turn. For on-line entry these values are in knots. For uploaded files the values are in miles per hour. The acceptable range of values for approach speed is 100 to 300 knots. The acceptable range for departure speed is 0 to 300 knots. Any values outside these ranges will generate an error.

Arrival runway occupancy time is the time from when an arrival crosses the runway threshold until it turns off the runway. There is one such value defined for VMC and one for IMC. *Departure runway occupancy time* is the time from when departure roll starts until the aircraft is no longer over the runway. Both times are in minutes. Acceptable values for arrival runway occupancy time are 0 to 3 minutes. Acceptable values for departure runway occupancy time is 0 to 4 minutes. Any values outside these ranges will generate an error.

Positional uncertainty to ATC refers to the controllers' uncertainty in actual aircraft position given the position reported by radar to the control tower. A value of 0.25 nautical miles reflects current technology. In uploaded files, this value should be in statute miles. A negative value will generate an error message.

Percentage of this class in airport traffic gives the fraction of the airports operations that involve aircraft of this class. ASAC checks that the sum over all classes is 1.00.

Standard deviation, for each item for which it is available, refers to the combined uncertainty in an individual aircraft's performance and the variations among different aircraft within a class. In all fields where a standard deviation is required, the standard deviation must be less than 1/5 of the corresponding mean value for that item.

Once the steps for one of the above choices for inputting aircraft class definitions has been completed, the model will automatically lead the user to the next input component.

Aircraft Separation Matrices

As in the previous component, the File Locator (Screen 3) is the first screen to appear, offering the user the following three similar choices:



Screen 3

- "Find Aircraft Separation Matrices File on Server" enables the user to select a file that is available on the ASAC system. This file may be used as is, or it may be edited and saved. After selecting "Find Aircraft Separation Matrices File on Server" and clicking on "CONTINUE", a list of available files is displayed. Select a file from the list box, then click on "CONTINUE". The user may next click on "VIEW/EDIT FILE" or "CONTINUE". If "VIEW/EDIT FILE" is selected, a screen with editable data fields, similar to Screen 4, will be displayed. At this point the user may make changes to the information or accept the information by clicking on "CONTINUE". The next screen allows

the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on “SAVE CHANGES” for any changes made. The file will be saved with the given name in the user’s ASAC directory. Alternatively, the user may click on “CONTINUE” if there are no changes.



Airport Capacity Model Aircraft Separation Matrices Builder

Enter the separation, in nautical miles, for each aircraft class. There are three grids, one each for VMC1, VMC2, and IMC. Press RESET to restore original values.

VMC1 Separations Leading Aircraft

	757	large	heavy
757	<input type="text"/>	<input type="text"/>	<input type="text"/>
large	<input type="text"/>	<input type="text"/>	<input type="text"/>
heavy	<input type="text"/>	<input type="text"/>	<input type="text"/>

VMC2 Separations Leading Aircraft

	757	large	heavy
757	<input type="text"/>	<input type="text"/>	<input type="text"/>
large	<input type="text"/>	<input type="text"/>	<input type="text"/>
heavy	<input type="text"/>	<input type="text"/>	<input type="text"/>

IMC Separations Leading Aircraft

	757	large	heavy
757	<input type="text"/>	<input type="text"/>	<input type="text"/>
large	<input type="text"/>	<input type="text"/>	<input type="text"/>
heavy	<input type="text"/>	<input type="text"/>	<input type="text"/>

CONTINUE

RESET

Screen 4

-
- ◆ “Build New Aircraft Separation Matrices File” enables the user to develop a file with customized information, involving separation of aircraft, by class, during different meteorological conditions (Screen 4). After entering data in the fields, click on “CONTINUE”. The next screen allows the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on “SAVE FILE” in order to save the new file.
 - ◆ “Upload Aircraft Separation Matrices File to Server” enables the user to use a file from their own computer. **This option *must* be selected if there are more than seven classes.** Follow the instructions that are listed on the screen for this process.

Uploaded input file format. The uploaded file should have one separation matrix for each of the three meteorological conditions. Each separation matrix consists of one row (line) per aircraft class. The order of the rows corresponds to the order in which classes were defined. The row for each class has a value for every class, separated by tabs. The value is the terminal area separation required when the row class is following each of the others. For on-line entry this value is in nautical miles. For uploaded files the values are in statute miles. The acceptable range of values is 1.5 to 7.0 nautical miles. Any values outside of this range will generate an error.

The user may add comment lines to the uploaded file. Each comment line begins with the # character in the first column.

Once the steps for one of the above choices for inputting aircraft separation matrices has been completed, the model will automatically lead the user to the next input component.

Operating Environment

As with the other input components, a File Locator screen (Screen 5) is the first to appear for this input component. The following four choices are available:



Screen 5

- ◆ “Use Default Operating Environment File” brings the user to a screen that offers the choices “VIEW/EDIT FILE” or “CONTINUE”. At this point the user may elect to either view the available information by clicking on “VIEW/EDIT FILE” (which displays a screen similar to Screen 6), and then edit it if changes are deemed necessary. The next screen allows the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on “SAVE CHANGES” for any changes made. The file will be saved with the given name in the user’s ASAC directory. Alternatively, the user may click on “CONTINUE” if there are no changes.



Screen 6

- ◆ “Find Operating Environment File on Server” enables the user to select a file that is available on the ASAC system. This file may be used as is, or it may be edited and saved. After selecting “Find Operating Environment File on Server” and clicking on “CONTINUE”, a list of available files is displayed. Select a file from the list box, then click on “CONTINUE”. The user may next click on “VIEW/EDIT FILE” or “CONTINUE”. If “VIEW/EDIT FILE” is selected, a screen with editable data fields, similar to Screen 6, will be displayed. At this point the user may make changes to the information. The next screen allows the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on “SAVE CHANGES” for any changes

made. The file will be saved with the given name in the user's ASAC directory. Alternatively, the user may click on "CONTINUE" if there are no changes.

- ◆ "Build New Operating Environment File" enables the user to develop a file with customized information. A screen similar to Screen 6 is displayed. Once changes have been made click on "CONTINUE". The next screen allows the user to assign a name to the file. A default name based on the session name is provided. After entering a file name, if desired, click on "SAVE CHANGES" for any changes made. The file will be saved with the given name in the user's ASAC directory. Alternatively, the user may click on "CONTINUE" if there are no changes.
- ◆ "Upload Operating Environment File to Server" enables the user to use a file from their own computer. Follow the instructions that are listed on the screen for this process.

Uploaded input file format. Each field is on a separate line. The fields, in order, are:

- ◆ communications delay
- ◆ communications delay standard deviation
- ◆ common approach path length
- ◆ minimum distance before turn
- ◆ wind uncertainty (standard deviation of wind speed)
- ◆ wake vortex hold time
- ◆ wake vortex after heavy departure rule flag
- ◆ IMC Departure release distance
- ◆ use IMC Departure release distance rule
- ◆ meteorological condition definitions

Communications delay is the time from when a departure clearance is issued by the air traffic controller until takeoff roll begins. Time is in minutes. Acceptable values are 0 to 1 minutes. The standard deviation may not exceed 1/5 of the mean. Any values outside these ranges generate an error.

Common approach path length is the distance over which aircraft fly in-trail in approaching a runway. **Minimum distance before turn** is the distance over which departures are in-trail from a runway. Units are in nautical miles for online entry and statute miles for uploads. Negative values generate an error.

Wind uncertainty refers to the variability of wind speed *over the common approach path*. It does *not* refer to variations in wind speed over time. The ASAC Airport Delay Model uses actual wind data; hence, wind variations over time (as well as temporal correlation) are accounted for directly.

Wake vortex hold time is the time from when an aircraft that is “heavy” (see aircraft class definitions) departs until the time when the next departure clearance on the same runway may be issued. The time unit is minutes. The acceptable range is 0 to 3 minutes. Any values outside these ranges generate an error. This value is used only if the **wake vortex after heavy departure rule flag** is set. For uploaded files, a value of 1 indicates that the hold time rule should be used; 0 indicates that this rule should be ignored.

IMC departure release distance is the minimum distance from the runway threshold that an arriving flight may be while a departure is still permitted from that runway. This rule is only used when the runway is not visible to the arriving flight at two miles distance. Units are in nautical miles for online entry and statute miles for uploads. The acceptable range is 0 to 2 nautical miles. Any values outside these ranges generate an error. This rule is used in capacity computations only if the **use IMC departure release distance rule** flag is set. For uploaded files a value of 1 indicates that the release distance rule should be used; 0 indicates that this rule should be ignored.

The last data item only needs to be provided in uploaded files; the ASAC system adds this information to data files created online. The **meteorological condition definitions** give the ceiling and visibility minima for VMC1, VMC2, IMC1, and IMC2. The units are hundreds of feet for ceiling and hundredths of miles for visibility. The definitions are particular to each airport and should not be changed. For Detroit Metropolitan Wayne County Airport (DTW) the following line should be input, with values separated by the tab character:

#Minimum ceiling visibility for VMC1, VMC2, IMC1, IMC2

45 500 10 300 2 34 2 30

The user may add comment lines to the uploaded file by inserting the character # in the first column of the line; any such lines are ignored by ASAC.

Runway Component

This is the final input component of the ASAC Airport Capacity Model. The following four choices are available at the first screen (Screen 7) within this component:



Screen 7

- ◆ "Use Default Runway Configuration File" leads the user immediately to running the ASAC Airport Capacity Model (see Running the Airport Capacity Model subsection).
- ◆ "Find Runway Configuration File on Server" displays a screen that offers the user a choice of files. Select a file and click on "CONTINUE". The next step will be to run the ASAC Airport Capacity Model (see Running the Airport Capacity Model subsection).
- ◆ "Build New Runway Configuration File" enables the user to customize the model with information on minimum ILS ceiling and visibility (Screen 8). The user may assign a name to this new file by entering one in the box at the top of the screen. A default name based on the session name is provided. Once changes have been made click on "CONTINUE". The next step will be to run the ASAC Airport Capacity Model (see Running the Airport Capacity Model subsection).

- ◆ “Upload Runway Configuration File to Server” enables the user to incorporate a file of information from their system into the model. Follow the instructions that are listed on the screen for this process.

Make desired changes and press **CONTINUE** to save.

New Runway File Name:

Runway Name: **3L**

ILS Minimum Ceiling:

ILS Minimum Visibility:

Heading: **34.3**

Runway Name: **3C**

ILS Minimum Ceiling:

ILS Minimum Visibility:

Heading: **34.3**

Runway Name: **3R**

ILS Minimum Ceiling:

ILS Minimum Visibility:

Heading: **34.3**

Runway Name: **21L**

ILS Minimum Ceiling:

ILS Minimum Visibility:

Heading: **214.3**

Screen 8 - (First half)

Runway Name:	21C
ILS Minimum Ceiling:	<input type="text" value="-1"/>
ILS Minimum Visibility:	<input type="text" value="50"/>
Heading:	214.3
<hr/>	
Runway Name:	21R
ILS Minimum Ceiling:	<input type="text" value="3"/>
ILS Minimum Visibility:	<input type="text" value="95"/>
Heading:	214.3
<hr/>	
Runway Name:	27L
ILS Minimum Ceiling:	<input type="text" value="2"/>
ILS Minimum Visibility:	<input type="text" value="50"/>
Heading:	274.7
<hr/>	
Runway Name:	27R
ILS Minimum Ceiling:	<input type="text" value="2"/>
ILS Minimum Visibility:	<input type="text" value="45"/>
Heading:	274.3
<input type="button" value="CONTINUE"/>	
<hr/>	

Screen 8 - (Second half)

Uploaded input file format. The default input file for DTW is reproduced below, along with the comments describing each field. All data values on the same line should be separated by the tab character. ***The underlined values in boldface must be entered exactly as shown in an uploaded file. Failure to do so will invalidate the delay model results.***

```
# number of runways
8
# the data for each runway appear on a single line as tab-separated values
# Runway name ILS minimum ceiling ILS minimum visibilityHeading
3L -1 11 34.3
3C -1 11 34.3
3R -1 11 34.3
21L -1 11 214.3
21C -1 11 214.3
```

21R -1 11 214.3
27L 2 50 274.7
27R 2 45 274.3
Magnetic deviation
-5.6

The *ILS minimum ceiling* and *ILS minimum visibility* for each runway give the values below which this runway cannot be used. Ceiling minima are in hundreds of feet; visibility minima are in hundredths of miles. A value of -1 indicates that this item does not constrain the runway usage. The units are hundreds of feet for ceiling, and hundredths of miles for visibility.

Magnetic deviation gives the variation, in degrees, of local headings from true headings. A negative value is used for deviations to the West.

Running the Airport Capacity Model

Running the ASAC Airport Capacity Model is contingent upon completing all four input components of the model. The actual running of the model automatically follows the end of the fourth input component.

The first screen to appear lists the files from the input components (aircraft class definitions, aircraft separation matrices, operating environment and runway) that will be used in the model. If any of these values are in error, the user can use the “Back” feature of their browser to return to a previous step, and correct the entry. Once the user accepts the files that will be used, click on “RUN AIRPORT CAPACITY MODEL”.

The next screen (Screen 9) indicates that model execution has completed and lists the results of running the model, which are a file for the Airport Capacity Frontiers and an input file for the Airport Delay Model. Select the Airport Capacity Frontiers. Screen 10 gives a sample output. The number of configurations that are available will be indicated at the top, (in this case 4) followed by the runway configurations (example: 21L/21C/21R).



Screen 9

Location: ftp://ftp.asac.lmi.org/pub/Models/Output/test1.998.cap

```
# Number of configurations
```

```
4
```

```
# Configuration Name
```

```
21L/21C/21R
```

```
5
```

```
0      88
```

```
39     88
```

```
71     76
```

```
78     64
```

```
78     0
```

```
5
```

```
0      80
```

```
36     80
```

```
66     70
```

```
72     59
```

```
72     0
```

```
5
```

```
0      74
```

```
32     74
```

```
62     67
```

```
64     61
```

```
64     0
```

```
1
```

```
0      0
```

```
1
```

```
# Configuration Name
```

```
3L/3C/3R
```

```
5
```

```
0      88
```

```
39     88
```

```
71     76
```

```
78     64
```

```
78     0
```

```
5
```

```
0      80
```

```
36     80
```

```
66     70
```

```
72     59
```

```
72     0
```

```
5
```

```
0      74
```

```
32     74
```

```
62     67
```

```
64     61
```

```
64     0
```

```
5
```

```
0      74
```

```
32     74
```

```
54     59
```

```
64     39
```

```
64     0
```

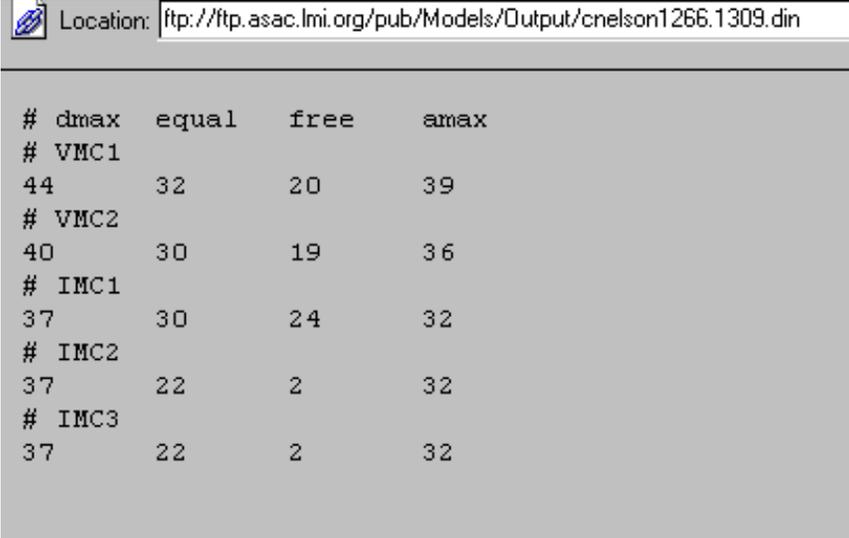
Screen 10 - (First half)

```
3
0      37
32     37
32     0
# Configuration Name
27L/27R
5
0      44
39     44
71     32
78     20
78     0
5
0      40
36     40
66     30
72     19
72     0
5
0      37
32     37
62     30
64     24
64     0
1
0      0
1
0      0
# Configuration Name
27L/27R/21R
3
0      44
78     44
78     0
3
0      40
72     40
72     0
3
0      37
64     37
64     0
1
0      0
1
0      0
```

Screen 10 - (Second half)

Each runway configuration has listed below it five sets of numbers, representing the capacity for that configuration in each of five weather conditions: VMC1, VMC2, IMC1, IMC2, and IMC3. The first number of each weather condition set is the number of points that can be found on the capacity frontier for that configuration in that weather condition. Each point on the capacity frontier is an (arrival rate, departure rate) pair. For example, the first number to appear immediately under the runway configuration 21L/21C/21R is a 5. This indicates there are 5 points for VMC1 on the frontier. The first point is “0,88”, indicating that when there are no arrivals, 88 departures per hour can be accommodated in this configuration. The second point is “39, 88”, indicating that 39 arrivals per hour can be accepted while maintaining the maximum departure rate of 88 per hour. In the first configuration (21L/21C/21R), the fourth and fifth set of numbers, for capacity in IMC2 and IMC3, respectively, indicate 1 pair of points that are “0,0”. This indicates that this runway configuration is not usable in IMC2 or IMC3.

Next, click on the “Back” button on your browser, to return to the screen that lists the output results of running the model. Select the Airport Capacity Model output file for the Delay Model. Screen 11 is an example of the results.



Location: <ftp://ftp.asac.lmi.org/pub/Models/Output/cnelson1266.1309.din>

#	dmax	equal	free	amax
# VMC1				
44		32	20	39
# VMC2				
40		30	19	36
# IMC1				
37		30	24	32
# IMC2				
37		22	2	32
# IMC3				
37		22	2	32

Screen 11

This file will become the **Input file** for the delay model. For the DTW model, the delay model input is five sets of single runway capacity values, one for each meteorological condition. Each set of values is tab delimited, and gives for that meteorological condition the maximum departure rate; departure/arrival rate when arrivals are spaced to accommodate a departure between each pair of arrivals; the number of departures per hour that can be accommodated without increasing arrival separations above the minimum required; and the maximum arrival rate.

If the user wishes to provide their own capacity file to the ASAC Airport Delay Model, it must conform to the format described in the previous paragraph.

AIRPORT DELAY MODEL

The user is automatically transferred to the ASAC Airport Delay Model if “Air Traffic Management Analysis” was selected from the ASAC Executive Assistant.

The ASAC Airport Delay Model may also be accessed from the “Model Wizard” at the following address:

<http://www.asac.lmi.org/access/model-wizard/>

or, through the ASAC home page by making these choices, in sequence:

- ◆ select “Quick Response System (QRS)”
- ◆ select “Enter”
- ◆ select “Model Server”
- ◆ select “Model Wizard”

However the Model Wizard is accessed, the ASAC Airport Delay Model is accessed by:

- ◆ selecting “ASAC Airport Delay Model” from the main dialog box
- ◆ clicking on “CONTINUE”

A very brief description of the delay model is given in the first screen. The user will also be asked for a “session name” which will then be assigned to the output data files created during this session. Clicking on “CONTINUE” at this point will start the user through the next few screens that develops the scenario under which the delay model is run.

DEVELOP SCENARIO

The first several screens in the delay model request information or actions from the user in the order that they are listed below. As each process is complete, proceed to the next screen by clicking on the “CONTINUE” button at the bottom of the screen.

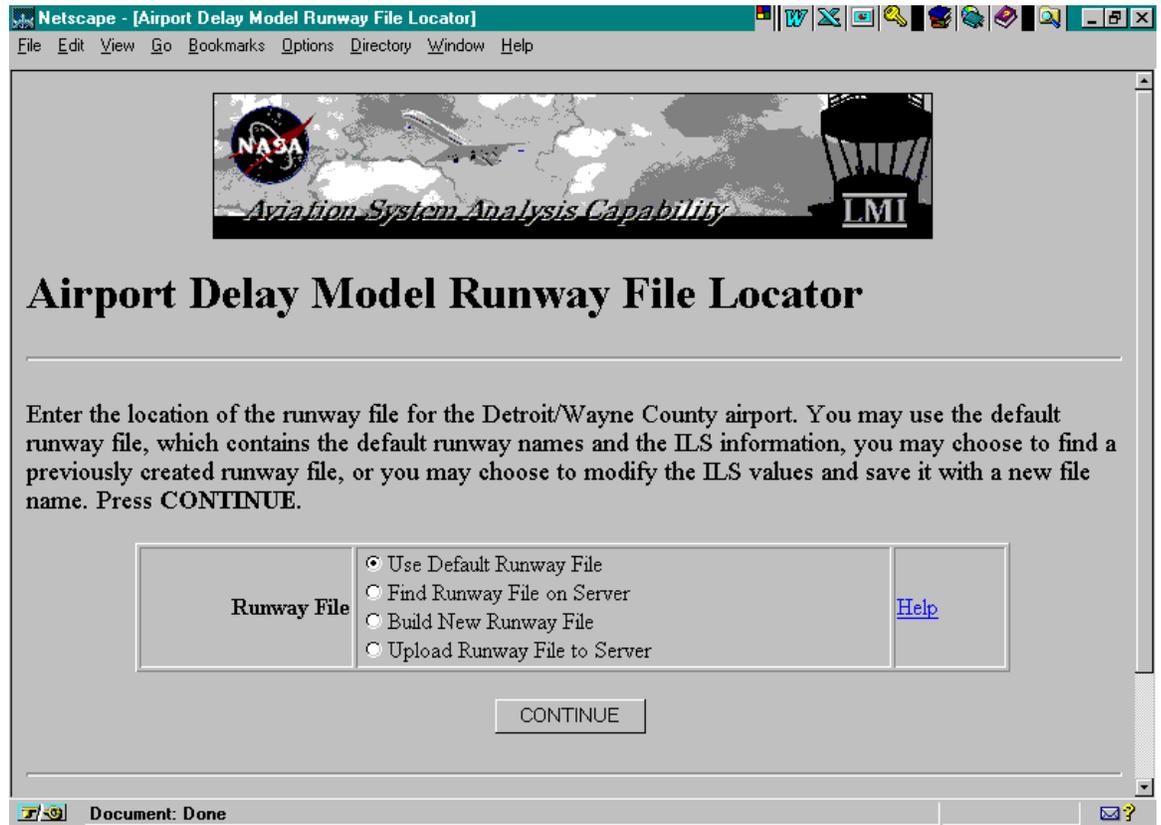
- ◆ the range of dates for the weather data;
- ◆ the inflation rate to be used for air traffic projections (The default uses a schedule based on the flights listed in the 1993 Official Airlines Guide (OAG); traffic growth projections are from the FAA’s Terminal Area Forecast (TAF). The 1993 hourly demands from the OAG are increased

by the traffic growth percentage selected before input to the delay model. The actual demands used can be viewed as part of the delay model output.);

- ◆ to either upload or find the ASAC Airport Capacity Model output file (using a tool called the Output File Locator. The format for uploaded files is described in the Running the Airport Capacity Model section);
- ◆ to locate the Runway File for the airport (using a tool called the Runway File Locator).

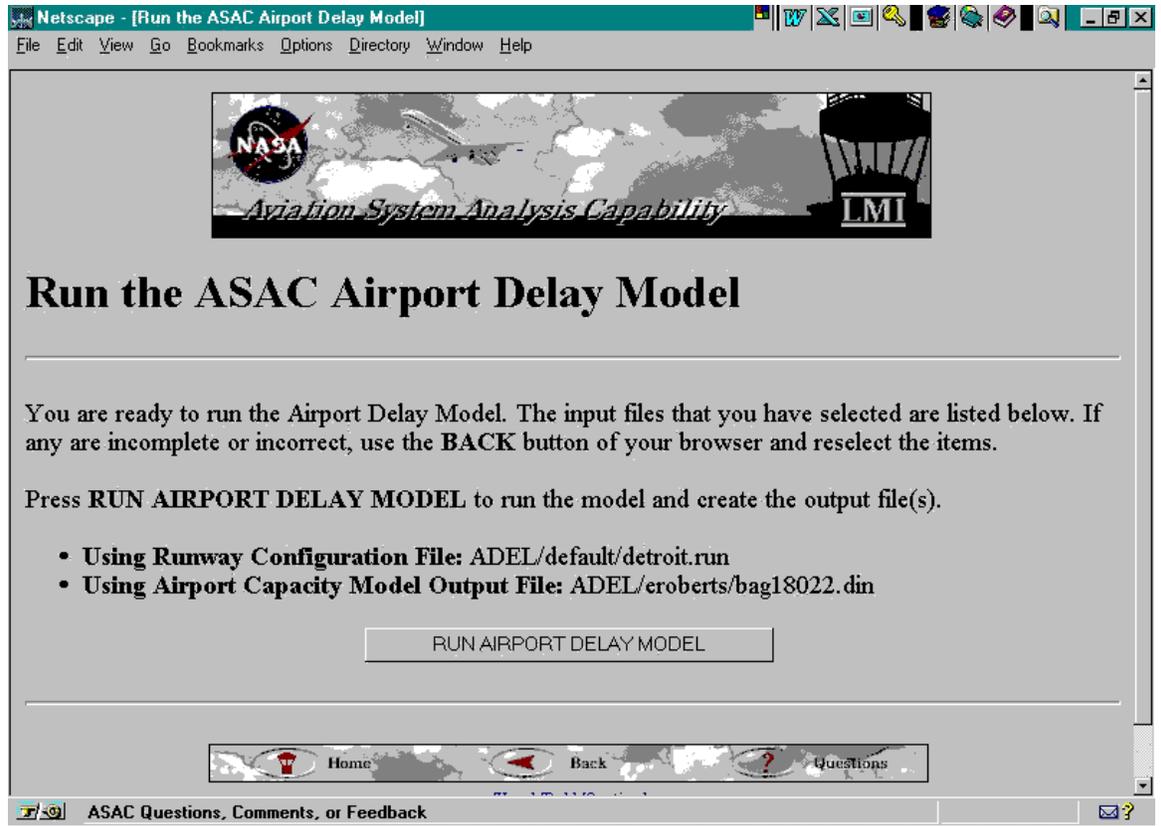
FILE LOCATOR

The File Locator procedure mentioned previously requires the user to make one from several choices for loading the runway file into the ASAC Airport Delay Model (Screen 12):



Screen 12

- ◆ “Use Default Runway File” uses a file available on the system. The user will be able to see which files have been selected and to run the delay model in the next step by clicking on “RUN AIRPORT DELAY MODEL” (Screen 13). The model results will appear on the next screen.



Screen 13

- ◆ “Find Runway File on Server” enables the user to access a file by using the Finder tool. This tool will list available files from which the user must select one. Select one, then click on “CONTINUE” to proceed to running the delay model. Click on the button marked “RUN AIRPORT DELAY MODEL” (Screen 13). The model results will appear on the next screen.
- ◆ “Build New Runway File” enables the user to customize the delay model inputs through use of a tool called Airport Delay Model Runway Configuration File Builder. The Builder will set up a file with ceiling, visibility and heading information by runway (similar to Screen 8). The user may assign a name to this new file by entering one in the box at the top of the screen. A default name based on the session name is provided. Clicking on “CONTINUE” will save these changes. The next step is to run the delay model by selecting “RUN AIRPORT DELAY MODEL” (Screen 13). The model results will appear on the next screen.
- ◆ “Upload Runway File to Server” enables the user to incorporate a file from their own computer by selecting and following the instructions as they appear on the screens. The format for uploaded files is described in the Airport Capacity Model User Guide section.

RUNNING THE AIRPORT DELAY MODEL

The ASAC Airport Delay Model will generate two outputs; the user may select either by clicking the mouse on their choice:

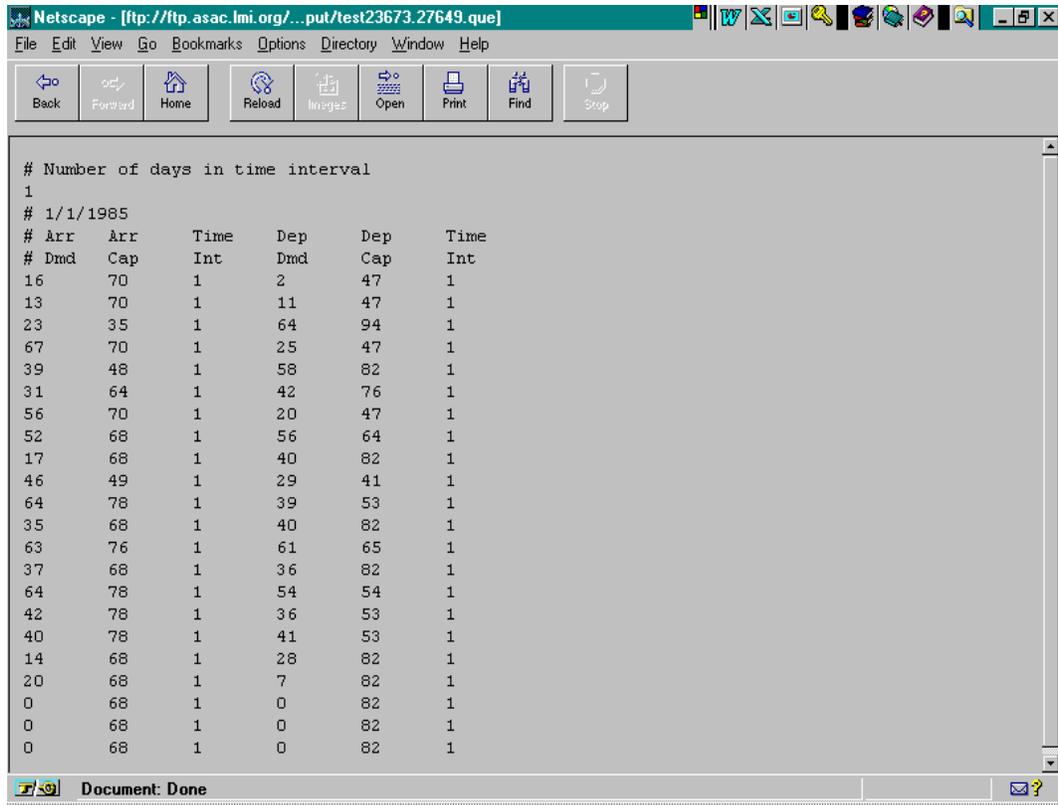
1. Delay in Minutes
2. Demand and Capacity Values used by queuing Engine

Selecting “1” will display Screen 14:

```
# Number of days in time interval
1
# Total minutes of arrival delay for time interval
3248
# Total arrival demand for time interval
739
# Average minutes of delay per flight
4
```

Screen 14

Whichever screen is chosen first, the second screen may be chosen by clicking on the browser’s “Back” button, then selecting the other configuration (in this case that is “2”, which appears in Screen 15).



Screen 15

The data appears in the following format:

Arrival	Arrival	Time	Departure	Departure	Time
<u>Demand</u>	<u>Capacity</u>	<u>Interval</u>	<u>Demand</u>	<u>Capacity</u>	<u>Interval</u>

Each line shows the values of demand and capacity used for one time interval, beginning with the first time interval of the day. The time interval is “1”, indicating that the time interval is 1 hour.

Appendix B

ASAC Runway Capacity Module

OVERVIEW

We have developed detailed model of runway operations and capacities. The parameters we used are listed in Table B-1.

Table B-1. Key Airport Modeling Parameters

Symbol	Definition
c	Communications time delay
δc	Variation in c
D	Length of common approach path
D_D	Distance until departures may turn
p_i	Fraction of operating aircraft that are type i
R_{Ai}	Arrival runway occupancy time of i th aircraft
δR_{Ai}	Variation in R_{Ai}
R_{Di}	Departure runway occupancy time of i th aircraft
δR_{Di}	Variation in R_{Di}
S	Miles-in-trail separation minimum
V_i	Approach speed of aircraft i
δV_i	Variation in approach speed of aircraft i
V_{Di}	Departure speed of aircraft i
δV_{Di}	Variation in departure speed of aircraft i
δW_i	Wind variation experienced by aircraft i
δX_i	Position uncertainty of aircraft i
μ_{ij}	Time increment imposed by controller, i behind j

We assume that each of the δc , δR_{Ai} , δR_{Di} , δV_i , δV_{Di} , δW_i , and δX_i variables are independent, normal, and random, with mean of zero and standard deviation of σ_c , σ_{RAi} , σ_{RD_i} , σ_{Vi} , σ_{VD_i} , σ_{Wi} , or σ_{Xi} as appropriate.

Our analysis takes a “controller-based view” of operations. That is, we assume that a person controls the aircraft, introducing time (or, equivalently, space) increments in operations streams to meet all applicable rules (e.g., miles-in-trail requirements) with specified levels of confidence. For example, consider the arrival–arrival sequence of Figure B–1.

Figure B-1. Time Phase for Arrivals When Follower Velocity > Leader Velocity

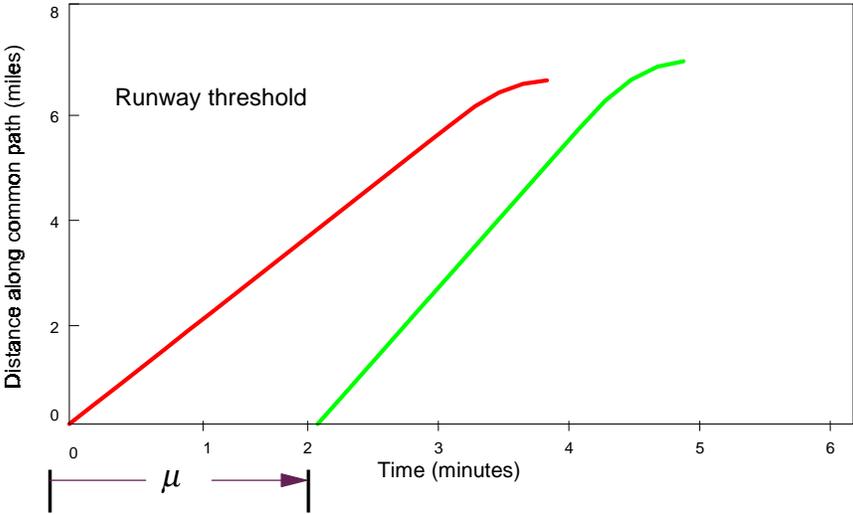


Figure B–1 shows the space–time trajectories of two arrivals. Zero distance is the beginning of the common approach path. In this model, the controller maneuvers the following aircraft so that it enters the common approach path a time μ after the lead aircraft enters it. (The controller may actually achieve this by bringing the following aircraft onto the common path when the lead aircraft has advanced a specified distance along the path.) The controller chooses the time interval μ in light of his or her knowledge of typical approach speeds for the two aircraft and of disturbances affecting their relative positions—winds, position uncertainties, variations in pilot technique. The controller does this to ensure that miles-in-trail requirements and runway occupancy rules are met, with assigned levels of confidence. This action of the controller, together with information on statistics of aircraft operating parameters and the disturbances to arrival operations (such as winds and position uncertainties), leads directly to statistics of operations and of runway capacity.

ARRIVALS ONLY

We consider first the controller-based paradigm for arrivals only. Two cases are important. The first, illustrated by Figure B–1, occurs when the mean approach speed of the following aircraft exceeds that of the leader.

Follower Velocity \geq Leader Velocity

For this case, the miles-in-trail constraint (distance) applies as the leader crosses the runway threshold. At that time, the leader's position is D . We derive a condition on the controller's interval, μ , to guarantee that the miles-in-trail requirement is met (i.e., that at the time the leader crosses the threshold, the follower is at least distance S away from the threshold, with a probability of 95 percent).

The position of the lead aircraft at time t , $X_L(t)$, is given by

$$X_L(t) = \delta X_L + (V_L + \delta V_L + \delta W_L)t, \quad [\text{Eq. B-1}]$$

and the position of the following aircraft at time t , $X_F(t)$, by

$$X_F(t) = \delta X_F + (V_F + \delta V_F + \delta W_F)(t - \mu). \quad [\text{Eq. B-2}]$$

The leader crosses the runway threshold at time t_{LO} , given by

$$t_{LO} = \frac{D - \delta X_L}{V_L + \delta V_L + \delta W_L}.$$

At time t_{LO} , the follower is at $X_F(t_{LO})$, given by

$$X_F(t_{LO}) = \delta X_F + (V_F + \delta V_F + \delta W_F) \left(\frac{D - \delta X_L}{V_L + \delta V_L + \delta W_L} - \mu \right). \quad [\text{Eq. B-3}]$$

We wish to derive a condition on μ , to make $D - X_F(t_{LO}) \geq S$ with a probability of at least 95 percent. To keep the problem tractable, we assume that all disturbances are of first order and make Equation B-3 linear. When made linear, Equation B-3 becomes

$$X_F(t_{LO}) = \delta X_F + \frac{DV_F}{V_L} \left(1 + \frac{\delta V_F + \delta W_F}{V_F} - \frac{\delta X_L}{D} - \frac{\delta V_L + \delta W_L}{V_L} \right) - \mu V_F \left(1 + \frac{\delta V_F + \delta W_F}{V_F} \right). \quad [\text{Eq. B-4}]$$

In this linear approximation, $X_F(t_{LO})$ is a normal random variable of mean

$$\frac{DV_F}{V_L} - \mu V_F$$

and variance

$$\sigma_1^2 = \frac{D^2 V_F^2}{V_L^2} \left(\frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} + \frac{\sigma_{XL}^2}{D^2} + \frac{\sigma_{VL}^2 + \sigma_{WL}^2}{V_L^2} \right) + \mu^2 V_F^2 \frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} + \sigma_{XF}^2. \quad [\text{Eq. B-5}]$$

The condition that $D - X_F(t_{LO}) \geq S$, with probability at least 95 percent, may then be stated as

$$\frac{DV_F}{V_L} - \mu V_F + 1.65 \sigma_1 \leq D - S \quad [\text{Eq. B-6}]$$

or

$$\mu \geq \frac{D}{V_L} - \frac{D - S}{V_F} + \frac{1.65 \sigma_1}{V_F}. \quad [\text{Eq. B-7}]$$

Equation B-7 gives, in essence, the desired condition. As that equation stands, μ appears on both sides of the inequality. Straightforward manipulations lead to an explicit condition on μ , which may be written

$$\mu = \frac{A + \sqrt{A^2 B^2 + C^2 (1 - B^2)}}{1 - B^2} \quad [\text{Eq. B-8}]$$

where

$$A \equiv \frac{D}{V_L} - \frac{D - S}{V_F}, \quad [\text{Eq. B-9}]$$

$$B^2 \equiv 1.65^2 \left\{ \frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} \right\} \quad [\text{Eq. B-10}]$$

and

$$C^2 \equiv \frac{1.65^2}{V_F^2} \left\{ \frac{D^2 V_F^2}{V_L^2} \left(\frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} + \frac{\sigma_{XL}^2}{D^2} + \frac{\sigma_{VL}^2 + \sigma_{WL}^2}{V_L^2} \right) + \sigma_{XF}^2 \right\}. \quad [\text{Eq. B-11}]$$

To determine numerical values of the smallest μ that meet Equation B-7, the iterative scheme

$$\mu_{n+1} = \frac{D}{V_L} - \frac{D - S}{V_F} + \frac{1.65 \sigma_1(\mu_n)}{V_F},$$

where $\sigma_1(\mu)$ is defined by Equation B-5, is convenient.

Now, let us develop a condition on μ that will guarantee that the follower aircraft does not cross the runway threshold until the leader has left the runway, with a probability of 98.7 percent. The leader will exit the runway at time

$$t_{LX} = t_{LO} + R_{AL},$$

and the follower will cross the threshold at time t_{FO} , given by

$$t_{FO} = \frac{D - \delta X_F}{V_F + \delta V_F + \delta W_F} + \mu. \quad [\text{Eq. B-12}]$$

Linearizing as above, we find that in the linear approximation $t_{FO} - t_{LX}$ is a normal random variable with mean

$$\frac{D}{V_F} + \mu - \frac{D}{V_L} - R_{AL}$$

and variance

$$\sigma_2^2 = \frac{D^2}{V_F^2} \left(\frac{\sigma_{XF}^2}{D^2} + \frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} \right) + \frac{D^2}{V_L^2} \left(\frac{\sigma_{XL}^2}{D^2} + \frac{\sigma_{VL}^2 + \sigma_{WL}^2}{V_L^2} \right) + \sigma_{RAL}^2. \quad [\text{Eq. B-13}]$$

It follows that the condition on μ for the follower not cross the threshold until the leader has exited the runway; that is, $t_{FO} - t_{LX} > 0$ with a probability of 98.7 percent, is

$$\mu \geq \frac{D}{V_L} - \frac{D}{V_F} + R_{AL} + 2.215\sigma_2. \quad [\text{Eq. B-14}]$$

The controller will, in effect, impose that value of time interval μ that is the smallest μ satisfying both Equations B-7 and B-14.

Given μ , the time between threshold crossings of successive arrivals is, in our approximation, a normal random variable of mean

$$\frac{D}{V_F} - \frac{D}{V_L} + \mu \quad [\text{Eq. B-15}]$$

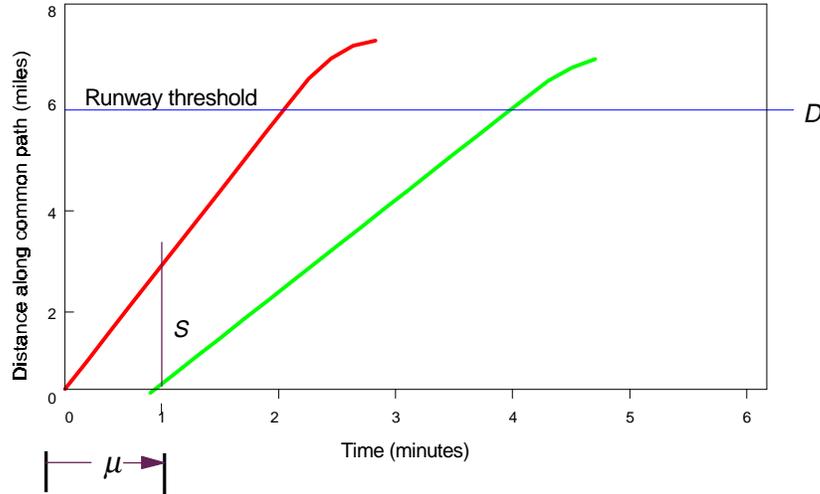
and variance

$$\sigma_3^2 = \frac{D^2}{V_F^2} \left(\frac{\sigma_{XF}^2}{D^2} + \frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} \right) + \frac{D^2}{V_L^2} \left(\frac{\sigma_{XL}^2}{D^2} + \frac{\sigma_{VL}^2 + \sigma_{WL}^2}{V_L^2} \right). \quad [\text{Eq. B-16}]$$

Follower Velocity < Leader Velocity

When the follower's approach speed is slower than the leader's, in the controller-based view the controller will bring the follower onto the common path after the leader has advanced a distance S along it, as illustrated in Figure B-2.

Figure B-2. Time Phase of Arrivals when Follower Velocity \leq Leader Velocity



In this case, the positions of the two aircraft as functions of time are again given by Equations B-1 and B-2. The miles-in-trail requirement is now that $X_L(\mu) - X_F(\mu) \geq S$, with a probability of at least 95 percent. As

$$X_L(\mu) - X_F(\mu) = \delta X_L + (V_L + \delta V_L + \delta W_L)\mu - \delta X_F \quad [\text{Eq. B-17}]$$

is a normal random variable of mean $V_L \mu$ and variance

$$\sigma_4^2 = \mu^2(\sigma_{V_L}^2 + \sigma_{W_L}^2) + \sigma_{X_F}^2 + \sigma_{X_L}^2, \quad [\text{Eq. B-18}]$$

it follows that the condition that the miles-in-trail requirement is met with a 95 percent confidence, is

$$\mu \geq \frac{S}{V_L} + 1.65 \frac{\sigma_4}{V_L}. \quad [\text{Eq. B-19}]$$

Equation B-19 may be written as a single condition on μ using Equation B-8 by replacing Equations B-9, B-10, and B-11 with the following new definitions:

$$A \equiv \frac{S}{V_L},$$

$$B^2 \equiv 1.65^2 \frac{\sigma_{VL}^2 + \sigma_{WL}^2}{V_L^2}.$$

and

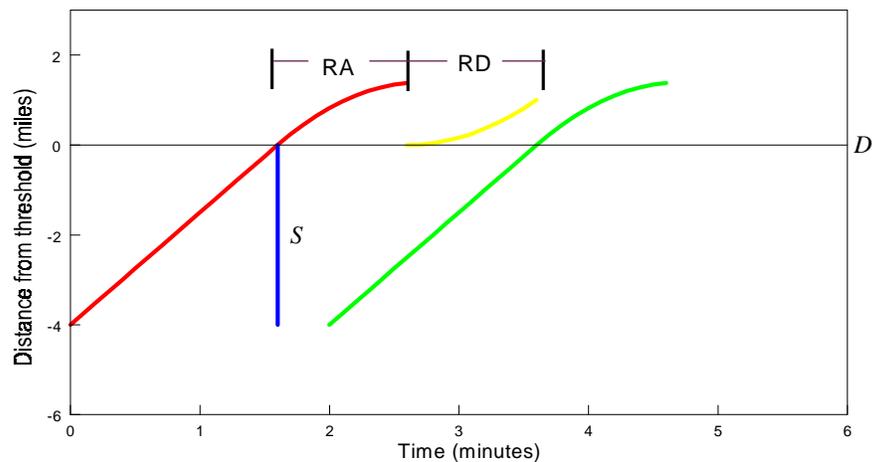
$$C^2 \equiv 1.65^2 \frac{\sigma_{XL}^2 + \sigma_{XF}^2}{V_L^2}.$$

The condition that the single-occupant rule is met with 98.7 percent confidence is derived exactly as is that condition for $V_F \geq V_L$ (i.e., the condition expressed in Equation B-14). Also, in the present case, Equations B-15 and B-16 yield the mean and standard deviation of interarrival times, given μ .

Arrival-Departure-Arrival-Departure Sequences

We can readily translate the results of the previous subsection to results for operations where there is a departure between successive arrivals by replacing R_{AL} with $R_{AL} + R_{DF}$, where R_{DF} is the departure runway occupancy time of the intervening departure aircraft. This case is illustrated by Figure B-3.

Figure B-3. Time Phase of Arrivals with Intervening Departure



It may be desirable to consider the effect of a communications lag c on the departure. If so, then R_{AL} is replaced by $R_{AL} + c + R_{DF}$.

STATISTICS OF MULTIPLE OPERATIONS

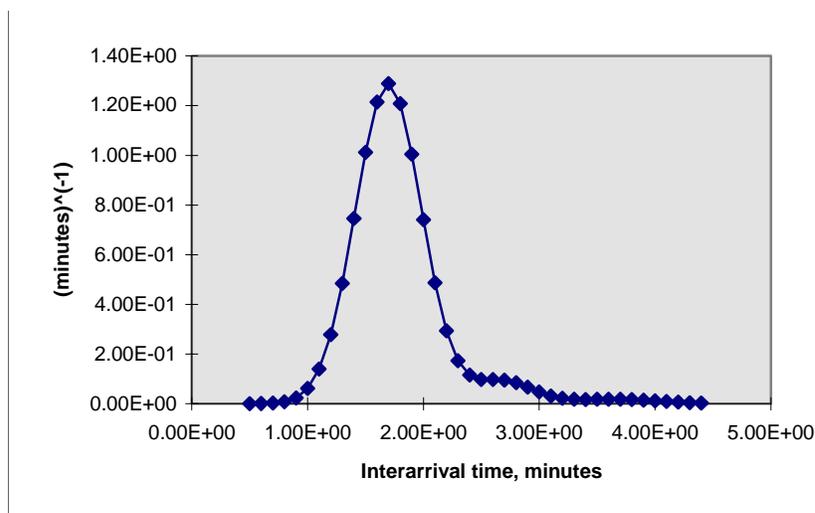
At this point, we have expressions for the means and variances of normal random variables representing interarrival times for a variety of cases. Now we will use these to generate statistics of multiple arrivals, or multiple arrivals and departures, that we can then use to produce capacity curves for single runways and combinations of runways.

First, we consider the statistics of sequences of arrivals only. Statistics of the overall interarrival time is determined by the mix of aircraft using the runway, with their individual values for the aircraft parameters of Table B-1. The fraction of the aircraft of type i in the mix is p_i . The previous results give the interarrival time for each pair as a normal random variable. Let the mean and standard deviation for aircraft type i following aircraft type j be μ_{ij} and σ_{ij} , respectively. Then the distribution function for overall interarrival time is

$$p_{AA}(t) = \sum_i \sum_j p_i p_j N(t; \mu_{ij}, \sigma_{ij}), \quad [\text{Eq. B-20}]$$

where $N(t; \mu, \sigma)$ denotes the normal probability distribution function. Obviously, the distribution of interarrival times is not normal. An example of an interarrival time distribution of the Equation B-20 type is shown in Figure B-4.

Figure B-4. Interarrival Time (Minutes)



As Figure B-4 shows, the interarrival time distribution is not necessarily monomodal.

The mean and variance of the interarrival time distribution, Equation B-20, can be computed straightforwardly. The results are

$$\langle t_{AA} \rangle = \sum_i \sum_j p_i p_j \mu_{ij} \quad [\text{Eq. B-21}]$$

and

$$\text{var}(t_{AA}) = \sum_i \sum_j p_i p_j (\sigma_{ij}^2 + \mu_{ij}^2) - \langle t_{AA} \rangle^2. \quad [\text{Eq. B-22}]$$

In principle, the analyst can compute exactly the distributions of total arrival times for all arrival sequences of arbitrary length and find exact values for the number of arrivals that can, with assigned confidence, be accommodated in 1 hour. These calculations involve sums of many terms, however, and this motivates a search for useful approximations.

Sums of normal random variables are normally distributed, and it is tempting to approximate the distribution of sequences of many arrivals in such a way. An all-arrival sequence with J_{ij} cases of aircraft of type i following aircraft of type j has a normal distribution whose parameters are easily computed. If the J_{ij} were chosen so that $J_{ij} = p_i p_j M$, where M is the sum of the J_{ij} , the resulting normal distribution would be a good approximation for the distribution of long arrival sequences. Unfortunately, for the aircraft mixes at some airports, some of the p_i values are only a few hundredths, so M would have to be several thousand for this approximation to be accurate.

Nevertheless, because much of our work to this point has been approximate, considering this “very large sequence”-limiting case does not seem unreasonable. In this approximation, then, the time t_M of M interarrival times has a normal distribution of mean $M\langle t_{AA} \rangle$ and variance

$$\text{var}(t_M) = M \sum_i \sum_j p_i p_j \sigma_{ij}^2. \quad [\text{Eq. B-23}]$$

This result suggests approximating the distribution of interarrival time with a normal distribution of mean $\langle t_{AA} \rangle$ and variance v_I given by

$$v_I = \sum_i \sum_j p_i p_j \sigma_{ij}^2. \quad [\text{Eq. B-24}]$$

The approximation of Equation B-24 can be used to compute the number of arrivals that can be accommodated in 1 hour with 95 percent confidence. That number M^* is determined by the condition

$$(M^* - 1) \langle t_{AA} \rangle + 1.65 \sqrt{(M^* - 1)v_1} \leq 60$$

(only $M^* - 1$ interarrival times are required for M^* arrivals),¹ which leads to the all-arrival capacity of a single runway as $M^* = w^2 + 1$, where w is given by

$$w = -\frac{1.65\sqrt{v_1}}{2 \langle t_{AA} \rangle} + \sqrt{\left(\frac{1.65\sqrt{v_1}}{2 \langle t_{AA} \rangle}\right)^2 + \frac{60}{\langle t_{AA} \rangle}}.$$

To compute the expected number of arrivals we use

$$\langle M \rangle = \frac{60}{\langle t_{AA} \rangle}.$$

Runway Capacity Curve

At this point, we have one point on the single runway capacity curve, the one corresponding to all arrivals and no departures. We can generate others.

The distribution function of Figure B-4 suggests that there is a significant probability of interarrival times being large enough to accommodate a departure. We can compute the number of “free” departures in a stream of $\langle M \rangle$ arrivals. These are departures that can be accommodated without introducing additional separations into the arrival stream, in this way: the distribution of interarrival time is given by Equation B-20. We assume that departure runway occupancy time, arrival runway occupancy time, and communications delay are normal random variables of means $\langle R_D \rangle$, $\langle R_A \rangle$, $\langle c \rangle$ and standard deviations σ_{RD} , σ_{RA} , and σ_c . The difference $t - R_D - R_A - c$, where t is the interarrival time, is the excess time when a departure is released between two arrivals. (The lead arrival exits the runway in time R_A , and the departure exits the runway in time $R_D + c$.) The distribution of the excess time is

$$\begin{aligned} p(t - R_A - R_D - c) &= N(-\langle R_A \rangle - \langle R_D \rangle - \langle c \rangle, \sqrt{\sigma_{RD}^2 + \sigma_{RA}^2 + \sigma_c^2}) \otimes \sum_i \sum_j p_i p_j N(\mu_{ij}, \sigma_{ij}) \\ &= \sum_i \sum_j p_i p_j N(\mu_{ij} - \langle R_D \rangle - \langle R_A \rangle - \langle c \rangle, \sqrt{\sigma_{RD}^2 + \sigma_{ij}^2 + \sigma_{RA}^2 + \sigma_c^2}), \end{aligned} \quad [\text{Eq. B-25}]$$

¹This derivation is valid for a single hour, considered in isolation. To compute the long-run average replace $M^* - 1$ by M^* .

where the symbol \otimes denotes convolution.² The probability that $t - R_D - R_A - c$ is positive, i.e., the probability that a free departure is possible between any random pair of arrivals, is given by

$$p_+ = 1 - \sum_i \sum_j p_i p_j C(0, \mu_{ij} - \langle R_D \rangle - \langle R_A \rangle - \langle c \rangle, \sqrt{\sigma_{RD}^2 + \sigma_{RA}^2 + \sigma_c^2 + \sigma_{ij}^2}) \quad [\text{Eq. B-26}]$$

where $C(t, \mu, \sigma)$ is the normal cumulative probability function. This value is readily computed. Then the analyst may determine the number $\langle N \rangle$ of positive values $t - R_D - R_A - c$ to be expected, in $\langle M \rangle$ draws, from the binomial distribution for probability p_+ .

Under IMC2 or IMC3 weather conditions, current FAA procedures require that departures be held if an arriving aircraft is within a certain distance of the runway threshold. (This distance is now 2 miles.) In our model, this has the effect of reducing the time available for “free” departing aircraft. Since the trailing arrival travels a distance less than the full length of the common path, the uncertainties embodied in Equation B-26 are also reduced.

The appropriate modification to Equation B-26 is to reduce the mean time available for free departures by

$$\frac{D_T}{V_F},$$

where D_T is the distance from threshold after which departures must be held. The variance in Equation B-26 is reduced by

$$\frac{D_T(2 \times D - D_T)}{V_F^2} \left(\frac{\sigma_{VF}^2 + \sigma_{WF}^2}{V_F^2} \right)$$

A third point on the capacity curve, the point of equal numbers of arrivals and departures, may be computed by considering sequences of repeated arrival-departure

²To account for variations in departure runway occupancy time (ROT), the analyst may replace the single normal distribution of ROT with the distribution of departure ROT that would be found with K classes of departing aircraft, each with its own normal distribution of departure ROT. That is,

$$\sum_1^K q_i N(-\langle R_D \rangle_i, \sigma_{Di}),$$

where q_i denotes the fraction of departing aircraft that are of type i .

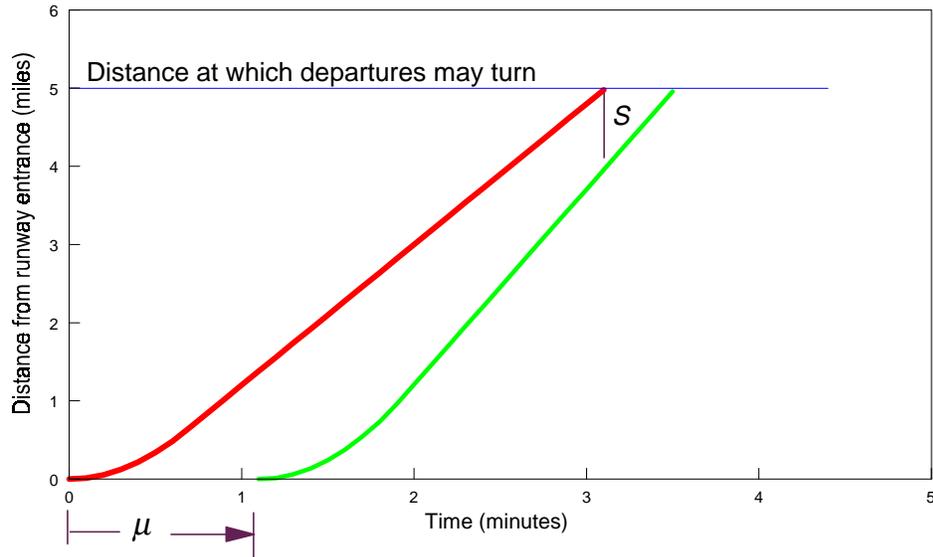
pairs, as described in the section Arrival–Departure–Arrival–Departure Sequences.

While the expressions for interarrival times and runway capacities developed previously in this appendix are somewhat lengthy, they are readily evaluated numerically.

DEPARTURES

Considerations similar to those for all arrival sequences, as treated in the section Arrivals Only, must be taken into account to develop to statistics of departures. The basic departure situation is shown in Figure B-5.

Figure B-5. Time Phase of Departures



We model the trajectory of a departing aircraft by specifying its position, $x(t)$, in terms of the parameters V_D and R_D , in this way:

$$x(t) = \begin{cases} \frac{1}{2} \frac{V_D}{R_D} t^2, & 0 < t \leq R_D \\ V_D t - \frac{1}{2} V_D R_D, & t \geq R_D \end{cases}.$$

This model approximates an actual takeoff roll and climb out by a trajectory with constant acceleration from rest to departure speed V_D , occurring in time R_D , followed by continuing departure at constant speed V_D .

We model controllers' actions on departures by the interdeparture time interval μ , which is the time interval between the start of the lead aircraft's takeoff roll to when a departure clearance is issued to the following aircraft. (The following aircraft begins takeoff roll at time $\mu + c$, where c models the delay to move into position.) We assume that, in effect, controllers adjust μ to give specified confidence that miles-in-trail requirements, and other separation requirements, are met.

Here again, the required control input varies, depending on whether the following aircraft is faster or slower than the lead aircraft. In the case of a faster follower, the constraining condition is that the separation requirement be met as the lead aircraft exits the system. At that time, the displacement of the lead aircraft is D_D , the distance to turn on departure. The displacement of the following aircraft must not be greater than $D_D - S_D$, where S_D is the minimum separation. After lengthy but straightforward steps, the controller finds that meeting this condition with 95 percent confidence imposes the condition

$$\mu \geq \frac{D_D}{V_{DL}} + \frac{1}{2}(R_{DL} - R_{DF}) - \frac{D_D - S_D}{V_{DF}} - c + \frac{1.65}{V_{DF}} \sqrt{\text{var}}$$

on μ . The quantity var in the inequality just above is

$$\begin{aligned} \text{var} = & \left(\frac{D_D}{V_{DL}} + \frac{1}{2}(R_{DL} - R_{DF}) - \mu - c \right)^2 \left(\sigma_{VDF}^2 + \sigma_{w_f}^2 \right) + \frac{V_{DF}^2}{V_{DL}^2} D_D^2 \frac{\sigma_{VDL}^2 + \sigma_{WL}^2}{V_{DL}^2} + \frac{V_{DF}^2}{4} \sigma_{RDL}^2 \\ & + \frac{1}{4} V_{DF}^2 \sigma_{RDF}^2 + V_{DF}^2 \sigma_C^2. \end{aligned}$$

The inequality may be reduced to an equivalent, explicit condition on μ . For numerical work, we find that iterative methods give the required values of μ conveniently.

When the follower departs more slowly than the leader, the separation minimums apply as the follower lifts off, unless D_D is sufficiently short that the leader can exit the system before the follower completes the takeoff roll. Applying the separation minimum as the follower lifts off leads to the condition

$$\mu \geq \frac{R_{DL}}{2} + \left(\frac{1}{2} \frac{V_{DF}}{V_{DL}} - 1 \right) R_{DF} - c + \frac{S_D}{V_{DL}} + 1.65 \sqrt{\text{var 1}} \quad (\text{inequality A})$$

where

$$\begin{aligned} \text{var } 1 = & \left(\mu + c + R_{DF} - \frac{1}{2} R_{DL} \right)^2 \frac{\sigma_{VDL}^2 + \sigma_{WL}^2}{V_{DL}^2} + \left(1 - \frac{V_{DF}}{2V_{DL}} \right)^2 \sigma_{RDF}^2 \\ & + \frac{1}{4} \left(\sigma_{RDL}^2 + R_{DF}^2 \frac{\sigma_{VDF}^2 + \sigma_{WF}^2}{V_{DL}^2} \right) + \sigma_C^2. \end{aligned}$$

Alternatively, the controller might impose a value of μ that caused the follower to lift off just as the leader exited the system. That would lead to

$$\mu \geq \frac{D_D}{V_{DL}} + \frac{1}{2} R_{DL} - R_{DF} - c + 1.65 \sqrt{\sigma_{RDF}^2 + \frac{D_D^2}{V_{DL}^2} \frac{\sigma_{VDL}^2 + \sigma_{WL}^2}{V_{DL}^2} + \frac{1}{4} \sigma_{RDL}^2 + \sigma_C^2}$$

(inequality B).

Controllers would impose the less restrictive of inequality A or inequality B. Finally, the single-occupant rule must be respected, which leads to

$$\mu \geq R_{DL} - c + 2.215 \sqrt{\sigma_{RDL}^2 + \sigma_C^2} \text{ (inequality C).}$$

For our model, when the follower is slower than the leader, we choose

$$\mu = \max [\min(\mu_A, \mu_B), \mu_C],$$

where μ_i is the lower bound on μ resulting from inequality i .

Appendix C

Combining Pareto Frontiers

The ASAC Airport Capacity Model develops capacity Pareto frontiers for individual runways and groups of interacting runways. The Pareto frontier describing the overall capacity of a configuration is derived from the combination of the component runway and runway group frontiers active in that configuration. In this appendix, we describe a general methodology for combining Pareto frontiers for configuration capacity.

Pareto frontiers can be combined pairwise, to arrive at a capacity frontier for the combination. In the event that a configuration has three runways or runway groups, the overall capacity Pareto frontier is arrived at by first combining any two Pareto frontiers, then combining the composite frontier just obtained with the third runway group's frontier. For more than three runway groups, each additional runway group frontier is combined with the composite frontier of the previously treated groups, until all have been incorporated; at each step, a pairwise combination is made.

Combining a pair of capacity Pareto frontiers is the fundamental operation in arriving at a configuration capacity Pareto frontier and is the subject of the remainder of this appendix.

A Pareto frontier is described by a set of points in the arrival-rate/departure-rate plane. We assume that the frontier is piecewise linear. The combined frontiers will also be piecewise linear. Let (a_i, d_i) ; $i = 1 \dots m$ and (b_j, e_j) ; $j = 1 \dots n$ be the set of (arrival, demand) rates of the Pareto frontiers to be combined. For each point we can compute the right-hand slope of the frontiers s_i and t_j , respectively:

$$s_i = \frac{d_{i+1} - d_i}{a_{i+1} - a_i}.$$

For the last pair on the frontier, the right-hand slope is undefined. A special value is stored in s_m to indicate this. The values t_j are computed analogously. The absolute value of the slope indicates the rate at which the controller must decrease departure capacity to increase arrival capacity from that operating point.

We begin constructing the combined frontier by generating the linear segments that represent the operational tradeoffs allowed by the constituent capacity curves. The upper envelope of these segments is the combined Pareto frontier. Each potential operational segment begins with a point (c_k, f_k) , $f_k = d_i + e_j$ and $c_k = a_i + b_j$ for some pair (i, j) . When operating at this point, the controllers have

two options for increasing arrival capacity at the expense of departure capacity: increase arrival rate from a_i on one complex or increase arrival rate from b_j on the other complex. The best choice is the former if $s_i > t_j$ and the latter otherwise. The end point of the segment is chosen to reflect this best possible tradeoff decision, i.e., $a_{i+1} b_j, d_{i+1} + e_j$ in the former case and $a_i + b_{j+1}, d_i + e_{j+1}$ in the latter. We also store the slope of the segment in its data structure, to avoid the need for recomputing it. We will denote this slope u_k . A pointer to the segment beginning at this segment's endpoint is also stored. (If there is more than one such segment, the one with the largest slope is pointed to.) We compute potential operational segments for each possible pairing of frontier points from the constituent capacity curves; thus the number of such segments is $N = m \times n$. We sort the segments by the left-hand edge arrival rate for later convenience.

Determination of the upper envelope of operational segments, the combined Pareto frontier, begins with the leftmost segment, the one beginning at $f_1 = d_1 + e_1$ and $c_1 = a_1 + b_1$. This point typically represents the all-departure capacity of the complexes being combined. For convenience we will denote this segment's endpoint by (c_2, f_2) . This segment is the *candidate segment* for the combined Pareto frontier. We then examine all other segments $[(c_k, f_k), (c_k', f_k'); u_k]$ that have arrival rate ranges overlapping the candidate segment. These are easily identified, as their left-hand edge arrival rate c_k is less than the right-hand edge arrival rate c_2 of the candidate segment. One of four cases can occur:

1. The right-hand end of the examined segment has an arrival rate c_k , that is less than right-hand end of candidate segment, and the departure rate of examined segment's right-hand edge f_k , which is less than the departure rate of the candidate segment for that arrival rate $d_1 + u_1(c_k - c_1)$. In this case, the examined segment is dominated: it lies entirely below the candidate segment. The examined segment can be discarded from any further consideration.
2. The right-hand end of the examined segment has an arrival rate c_k , that is less than the right-hand end of the candidate segment, and the departure rate of the examined segment's right-hand edge f_k , that is greater than the departure rate of the candidate segment for that arrival rate, $d_1 + u_1(c_k - c_1)$. In this case, the examined segment crosses the candidate segment. This is the most complex case, and we proceed as follows:
 - ◆ Compute the point of intersection between the two segments.
 - ◆ Set the left-hand edge of the examined segment to be this intersection point. (The portion of the examined segment to the left of the intersection is dominated and can be ignored.)

- ◆ Set the right-hand edge of the candidate segment to be the intersection point, and set the candidate segment's pointer to the (modified) examined segment.
- ◆ Create a new segment from the intersection point to the previous endpoint of the candidate segment. The slope of this new segment is the same as that of the candidate segment, and its pointer is set to the old pointer value of the candidate segment. This new segment, as it extends beyond the examined segment, may still be part of the combined Pareto frontier.

We continue comparing the revised candidate segment to unexamined segments that overlap its new extent.

3. The right-hand end of the examined segment has an arrival rate c_k , that is greater than the right-hand end of candidate segment, and the departure rate of the examined segment at the right-hand edge of the candidate segment c_2 , that is less than the departure rate of the candidate segment for that arrival rate $d_k + u_k(c_2 - c_k) < f_2$. In this case, the overlapping portion of the examined segment is dominated, but the remaining extent of the examined segment may still be part of the Pareto frontier. We do nothing in this case.
4. The right-hand end of the examined segment has an arrival rate c_k , that is greater than the right-hand end of the candidate segment, and the departure rate of the examined segment at the right-hand edge of the candidate segment c_2 , is greater than the departure rate of the candidate segment for that arrival rate $d_k + u_k(c_2 - c_k) < f_2$. In this case, as in case 2, the examined segment intersects the candidate segment. The difference is that the portion of the candidate segment to the right of the intersection is dominated and can be discarded. The procedure is the same as in case 2, except that the last step is not performed.

Once we have examined all overlapping segments, we know no segments are above the candidate segment. The endpoints of the candidate segment (perhaps modified during the search) are on the combined Pareto frontier. The next candidate segment is the one pointed to by the old candidate segment. The procedure is repeated for this new candidate segment. The procedure will end with a segment whose endpoint is the arrival capacity of the combination. After examining this segment, all other segments will either be part of the Pareto frontier or will have been discarded as dominated.

When the form of the Pareto frontier for the complexes to be combined is known, it is possible to specialize and simplify the procedure described here. Such specializations are used where possible.

Appendix D

Detroit's Airport Capacity Model

FAA controllers and managers at Detroit Metropolitan Wayne County Airport (DTW) informed us that the airport almost always operates in one of four configurations: 21L/21C/21R, 3L/3C/3R, 27L/27R, or 27L/27R/21R. (Operations in the last configuration require traffic on runway 27R to hold short of runway 21R.) Prevailing winds cause the 21 configuration to be by far the one most often used.

In the 21 configuration, 21L is used exclusively for arrivals and 21C exclusively for departures. The arrival and departure mix on 21R is adjusted to best accommodate demand. The 3 configuration is operated similarly, with 3R devoted to arrivals and 3C devoted to departures, with the mix on 3L adjusted in view of demand.

When the 27 configuration is in use, 27L is devoted to arrivals and the mix on 27R is adjusted to best accommodate demand. For the 27L/27R/21R configuration, both 27 runways accommodate arrivals only; runway 21R is devoted to departures. This configuration is used only in dry weather.

In most cases where a runway is used to balance capacity, the achieved arrival and departure rates on that runway are determined from the runway's Pareto frontier in such a way that the proportion of arrival demand and departure demand presented is equal to the achieved proportion of arrival and departure demand.

The exception to the above rule is when the 3 configuration is used. In the 3 configuration, two runways are used for arrivals (in IMC1 or better) and one for departures when the balancing mix would require an arrival rate exceeding the departure rate by more than 20 percent. When arrival demand is not so heavy, this runway is managed for an equal number of arrivals and departures. This scheme reflects the practice of controllers at DTW.

For an example of how the model determines capacity as a function of weather and demand, consider the following situation. The ceiling is 600 feet and visibility is 5 miles. Due to the low ceiling, we are in IMC1. Winds are from the north (blowing from heading 340°) at 13 knots. This creates a tailwind on the 21s in excess of the maximum of 8 knots, so the configuration 21L/21C/21R is not usable. During a departure push the arrival demand during the next hour is 23, and the departure demand is 64. The arrival/departure capacity of the usable configurations is 3L/3C/3R: 64/78; 27L/27R: 33/47; 27L/27R/21R: 66/47. Since the 3L/3C/3R configuration is best able to meet the predominant demand, departure traffic, it is the one selected.

Now consider the same weather conditions when there is an arrival push. Arrival demand in the next hour is 67, and departure demand is 25. During an arrival push, two runways of 3L/3C/3R are dedicated to arrivals, rather than using one for arrivals and one for both arrivals and departures as in a departure push. In the 27L/27R configuration, the runway used to balance traffic between arrivals and departures will be skewed toward accommodating arrivals. The configuration capacities are 3L/3C/3R: 66/47; 27L/27R: 66/24; 27L/27R/21R: 66/47. We see that even for the same weather conditions, the demand affects the configuration capacity. All of the configurations give equal arrival capacity during this arrival push. The 3L/3C/3R and 27L/27R/21R configurations allow the greatest departure capacity, so we would choose one of those. Since they have equal capacities, the choice is arbitrary.

Appendix E

Staggered Departure and Arrival Models

In this appendix we describe the ASAC Airport Capacity Model algorithm used to estimate the capacity of a parallel runway pair when there are spacing requirements between both aircraft using the same runway and between aircraft using one runway and aircraft using a parallel runway. This can occur when both runways are used for departures or when both runways are used for arrivals.

Unlike separation requirements for single runways, separation requirements in this situation between aircraft approaching the same runway cannot be derived by examining aircraft class pairs in isolation; the interdependence of traffic on the two runways requires, in general, knowledge of the entire sequence of operations to determine the separation required between any two aircraft approaching the same runway.

Since exact separations cannot be determined, except for a specific sequence of operations, the algorithm constructs upper and lower bounds on the separation time required between successive operations on one runway of the pair. The bounds are computed for each combination of following aircraft class and leader aircraft class (as in the single runway model). The bounds take into account the interaction with traffic on the other runway.

A user-controllable parameter determines how many historical operations are considered, and thus how much refinement is put into determining the separation bounds, so that capacity can be estimated to any desired degree of precision (at the expense of additional computation time). The capacity bounds of the runway are computed on the basis of the weighted average time between operations; the weighting factors account for the traffic mix on the targeted runway. Since we assume that operations alternate between runways, the capacities of both the targeted runway and the “other” runway will be the same. We can exploit this symmetry by computing the capacity bounds twice, one using each runway as the target. The computed bounds will generally differ, leading us to identify a best lower bound and a best upper bound on estimated capacity.

Here we discuss the capacity bounding algorithm from the perspective of departures. The staggered-operations capacity algorithm for arrivals is completely analogous.

MODELING DEPARTURE CAPACITY OF A PARALLEL RUNWAY PAIR

In modeling the interdeparture times on the target runway, we assume that a departure has just occurred on the other runway. To capture the separation times required between two aircraft on the target runway (aircraft of type i , following an aircraft of type j , which is next to depart), we need to consider also the aircraft of type l , which has just departed on the other runway, and the aircraft of type k , which is due to depart the other runway after the aircraft of type j departs the runway under consideration. The departure sequence is l, j, k, i . For conciseness we will refer to an aircraft of type x as simply aircraft x .

We define $\mu(i, j, k, l)$ to be the average time separation (in minutes) that the controller will apply to aircraft i following aircraft j on the same runway, when aircraft l has just departed the other runway and aircraft k is next to depart the other runway. We compute both upper and lower bounds on this separation.

The separation (in minutes) between i and j that we use to compute the runway's capacity is the weighted average

$$\mu_p(i, j) = \sum_{k,l} \mu(i, j, k, l) p_{xk} p_{xl},$$

where p_{xk} (p_{xl}) is the probability of aircraft k (l) on the other runway. Upper (lower) bounds on $\mu_p(i, j)$ are computed using the upper (lower) bounds on $\mu(i, j, k, l)$.

The hourly runway capacities are estimated by

$$capacity = \frac{60}{\sum_{i,j} \mu_p(i, j) p_i p_j},$$

where p_i and p_j are the probability of i and j on the targeted runway. Lower (upper) bounds on capacity are derived from the upper (lower) bounds on separation.

To develop the definition of $\mu(i, j, k, l)$, let us define two other separations. $\mu_s(i, j)$ is the single runway separation required for aircraft i following aircraft j . These are the same separations used in the single runway model. $\mu_x(i, k)$ is the separation required between aircraft i following a departure of aircraft k on the other runway. As in the single runway model, these separations are determined

from the controller's point of view, including time to account for uncertainties in wind, speed, and position. Let us define t_i as the time of departure of aircraft i .

Given that aircraft i departs after j on the target runway and k on the other runway, then by definition

$$t_i = \max[t_j + \mu_s(i, j), t_k + \mu_x(i, k)].$$

In general, the relative values of t_j and t_k (and hence t_i) depend on the unspecified history before flight l 's departure; however, under certain conditions, the separation $t_i - t_j$ —i.e., $\mu(i, j, k, l)$ —can be computed without knowledge of the prior history.

- ◆ *Markov Property.* For any sequence of departures l, j, k such that

$$\mu_s(k, l) \leq \mu_x(k, j) + \mu_x(j, l),$$

all prior history is irrelevant in determining

$$t_k = \mu_x(k, j) + t_j$$

and

$$t_i - t_j = \max[\mu_s(i, j), \mu_x(i, k) + \mu_x(k, j)].$$

- ◆ *Proof.* By definition $t_j \geq t_l + \mu_x(j, l)$, thus

$$t_j + \mu_x(k, j) \geq t_l + \mu_x(j, l) + \mu_x(k, j).$$

By hypothesis the right-hand side is greater than $\mu_s(k, l) + t_l$, leading to

$$t_j + \mu_x(k, j) \geq \mu_s(k, l) + t_l.$$

The two terms above are those whose maximum defines t_k , thus the value of t_k is known in terms of t_j . Substituting $t_j + \mu_x(k, j)$ for t_k in the maximum formula for t_i , and subtracting t_j from all terms leads to the final result. QED.

Another useful relationship is the following:

- ◆ *Parallelogram Property.* For any departure sequence l, j, k for which the Markov Property does *not* hold, if

$$\mu_s(i, j) + \mu_x(j, l) \geq \mu_s(k, l) + \mu_x(i, k)$$

then

$$t_i - t_j = \mu_S(i, j).$$

◆ *Proof.* From the defining maximum formula we note that

$$t_k - t_j = \max[\mu_S(k, l) - (t_j - t_l), \mu_X(k, j)].$$

Since $t_j - t_l \geq \mu_X(j, l)$, we have

$$t_k - t_j \leq \max[\mu_S(k, l) - \mu_X(j, l), \mu_X(k, j)];$$

and the assumption that the Markov Property is *not* true leads to

$$t_k - t_j \leq \mu_S(k, l) - \mu_X(j, l).$$

With this result in hand, let us examine the defining relation

$$t_i - t_j = \max[\mu_S(i, j), t_k - t_j + \mu_X(i, k)].$$

The second term in the maximum is less than

$$\mu_S(k, l) - \mu_X(j, l) + \mu_X(i, k),$$

by the inequality just obtained, and by hypothesis, this bound in turn is less than $\mu_S(i, j)$, leading to the final result.

BOUNDING SEPARATIONS

The two properties discussed in the previous section allow direct determination of the separation between i and j for some classes k and l . In these cases, we set both the upper and lower bound on separation to the known value. For those cases where neither property is of assistance, we now describe how to establish bounds on the separations.

The maximum separation between i and j occurs if the prior departure on the target runway does not delay flight j by any more than the cross-runway separation from flight l . In this case j is leaving as early as possible, considering that flight l preceded it on the other runway. If we set t_j to the lower bound, $t_l + \mu_X(j, l)$, and choose any arbitrary value for t_l , then the remaining departure times, including t_i , can be computed from the defining maximum formulae, and the upper bound on the separation between i and j can be computed.

The minimum separation between i and j occurs when j is forced to lag l by the maximum amount, because of prior history. If

$$\max_sep(j,l) = \max_m [\mu_s(j,m) - \mu_x(l,m)],$$

the largest value that t_j could take on is $t_l + \max_sep(j,l)$. Assuming an arbitrary value for t_l and this maximum value t_j allows computation of the remaining departure times and the lower bound on the separation between i and j .

Both the lower and the upper bounds computed above depend on l and k . The bounds independent of l and k are computed by weighted sums of these l, k -dependent terms.

CONSIDERING MORE HISTORY

The bounds of the previous section are based on the extreme case for prior history. These bounds can be refined by explicitly considering prior departure sequences. Let us denote the additional flights considered by $f_1, f_2, f_3, \dots, f_n$, each departing earlier than the previous one in the sequence. We will use F to denote the entire sequence. The flights with an odd index depart from the target runway; those with an even index depart from the other runway. The bounds on $\mu_p(i, j)$ are calculated as

$$\text{bound on } \mu_p(i, j) = \sum_{l,k,F} (\text{bound due to } l, k, F) p_{xl} p_{xk} \prod_{z=0}^{\lfloor \frac{n-1}{2} \rfloor} p_{f_{2z+1}} \prod_{z=1}^{\lfloor \frac{n-1}{2} \rfloor} p_{xf_{2z}}.$$

In practice, we may not need to consider the entire sequence F to bound $t_i - t_j$. If there is any subsequence f_{z+2}, f_{z+1}, f_z that satisfies the Markov Property, then we can determine f_z in terms of f_{z+1} . Given f_z and f_{z+1} we can determine all subsequent departure times, including the times of interest, t_i and t_j . Any arbitrary value of f_{z+1} will do. The capacity algorithm uses recursive code to add history if the Markov Property is not true for the last three flights in the current history F . If the Markov Property is true, the lower and upper bounds are set to the same (computable) value.

The model user can specify the maximum number of aircraft to add to the history F . The larger this maximum, the more accurate the bounds will be, but the longer the computations will take. If a particular history sequence has reached its maximum size without the Markov Property being true for some subsequence, then lower and upper bounds due to the sequence are computed.

Before explaining how the bounds are computed, we make the following observation:

- ◆ *Theorem.* If the Markov Property does not hold for any subsequence of k, j, l, F , then when f_{n-1} is at its earliest time, either all departure times within k, j, l, F are based only on same runway separations, or $t_i - t_j$ is independent of any further history.
- ◆ *Proof.* Since the Markov Property is not true for any subsequence, the cross-runway constraints are not binding on any subsequent flights in k, j, l, F when the last two flights in any subsequence occur at their earliest times. If additional history requires that some flight f_x depart later than its unconstrained earliest time, even when f_{n-1} is at its unconstrained earliest time—and at this history-constrained earliest possible time for f_x , $t_{f_x} + \mu_X(f_{x-1}, f_x) > t_{f_{x+1}} + \mu_S(f_{x-1}, f_{x+1})$, then all departure times after f_x (including t_i , and t_j) can be determined in terms of t_{f_x} . Furthermore, in this situation, adding additional history will not change the relative times of departures after f_x . If additional history would cause f_{n-1} to be later than its earlier time, this would cause f_x to be deferred by an equal increment, as by the assumption it is the accumulated same runway constraints from f_{n-1} back to f_x that have determined t_{f_x} . A later time for f_{n-1} may also activate some other cross-runway constraint, causing f_{x+1} to occur later, but by no more than the additional delay to f_x ; thus, f_x would continue to be a point from which later departure times can be computed. If there is no such f_x for the current history, k, j, l, F , this is equivalent to stating that all separations in k, j, l, F are determined by the same runway separations, μ_S , Q.E.D.

Now assume that the last flight added is not on the target runway. Then f_{n-1} is on the target runway. When f_{n-1} is at its earliest time, j is also at its earliest time. As the departure time of f_{n-1} is delayed, it may begin to delay flight j via the accumulated same runway separations. Thus, the upper bound on separation between i and j occurs when $t_{f_{n-1}} = t_{f_n} + \mu_X(f_{n-1}, f_n)$ the lower bound on $t_{f_{n-1}}$; the lower bound on separation occurs when $t_{f_{n-1}} = t_{f_n} + \max_sep(f_{n-1}, f_n)$ and the upper bound on $t_{f_{n-1}}$.

On the other hand, if the last flight added is on the target runway, then f_{n-1} is on the other runway. As the departure of f_{n-1} increases from its earliest time, it may cause flight k to depart later. The cross-runway constraint between i and k may force i to depart later, increasing the time between the departure of i and j . (By the theorem, delaying a flight on the other runway either will not change the departure time j or will increase the departure time of i and j equally.) Thus the upper bound on separation occurs when $t_{f_{n-1}}$ is at its upper bound, and the lower bound on separation occurs when $t_{f_{n-1}}$ is at its lower bound.

MODELING CURRENT FAA PROCEDURES

Modeling current procedures requires selecting appropriate values for μ_S and μ_X . Setting $\mu_S(i, j)$ is described in the single runway model description. We examine here appropriate values for μ_X .

Departures

One rule in existing procedures requires a 2-minute departure hold on either runway of a parallel pair separated by 2,500 feet or less after the departure of a heavy jet. So if k is a heavy jet, we set $\mu_X(i, k) = 2$; otherwise, to zero. This rule can be turned off by a user input.

A further restriction when both runways of a pair are used for departures occurs when visual separation cannot be applied when a departure is 1 mile from the threshold. In this case departures on the parallel runways must be released so as to achieve a 1-mile separation. The same departure logic used in the single runway model to ensure separation along a single departure path can be used to determine the time separation that the controller will apply in this situation. That logic only needs to be modified to reflect a 1-mile departure path and 1-mile separation criterion.

When ceiling or visibility requires the latter separation criterion to be used, the μ_X value for any pair is the maximum of that required for heavy jet separation and that required for the 1-mile separation.

Arrivals

Diagonal separation between arrivals to parallel runways may need to be applied in IMC. The diagonal separation required depends on the distance between the runway centerlines and the radar available to monitor aircraft positions.

Regardless of the particulars, the diagonal separation can be converted into an equivalent separation parallel to the runways, by elementary right-triangle trigonometry. (The diagonal separation requirement is the hypotenuse; the distance between the runway centerlines is one of the shorter sides. The equivalent lateral separation is the other shorter side, which can be solved for.) Once the equivalent lateral separation is determined, the same procedures used to determine single runway controller separations to achieve a miles-in-trail goal can be applied.

Appendix F

Abbreviations

AROT	Arrival Runway Occupancy Time
ASAC	Aviation Systems Analysis Capability
ASQP	Airline Service and Quality Performance
ATC	Air Traffic Control
DTW	Detroit Metropolitan Wayne County Airport
FAA	Federal Aeronautics Administration
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
OAG	Official Airline Guide
OASIS	Information System
OPSNET	Information System
QRS	Quick Response System
ROT	Runway Occupancy Time
TAF	Terminal Area Forecast
VMC	Visual Meteorological Conditions

