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Terminal Area Productivity Airport Wind Analysis and Chicago O'Hare Model Description

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April 1998

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Abstract

This paper describes two results from a continuing effort to provide accurate cost-benefit analyses of the NASA Terminal Area Productivity (TAP) program technologies. Previous tasks have developed airport capacity and delay models and completed preliminary cost benefit estimates for TAP technologies at 10 U.S. airports. This task covers two improvements to the capacity and delay models. The first improvement is the completion of a detailed model set for the Chicago O'Hare (ORD) airport. Previous analyses used a more general model to estimate the benefits for ORD. This paper contains a description of the model details with results corresponding to current conditions.

The second improvement is the development of specific wind speed and direction criteria for use in the delay models to predict when the Aircraft Vortex Spacing System (AVOSS) will allow use of reduced landing separations. This paper includes a description of the criteria and an estimate of AVOSS utility for 10 airports based on analysis of 35 years of weather data.

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Chapter 1
Overview

This task is the latest part of a continuing effort to provide accurate cost-benefit estimates for the technologies being pursued in the NASA Terminal Area Productivity Program (TAP). Previous tasks have developed airport capacity and delay models and completed preliminary cost benefit analyses of 10 U.S. airports. The current task was initially intended to investigate the benefits of Airborne Information for Lateral Spacing (AILS) technology. The task was redirected to improve the capacity and delay models.

There are two aspects to the model improvement effort. The first is completion of "detailed" models for the 10 airports and the second is addition of new features to the existing detailed models. The preliminary cost benefit results were obtained with a mix of models. The results for Boston were obtained with the model developed during the initial task. The Boston model is a "detailed" model, but its structure is unique. Results for Detroit, Atlanta, LaGuardia, Dallas, and Los Angeles were obtained with detailed models. Results for Chicago, New York Kennedy, Newark, and San Francisco were obtained using the more general LMINET models. A detailed model for Chicago was completed under the current task.

The second aspect of model improvement involves additions and modifications to the models to better estimate the details of the TAP technologies. One shortcoming of the current models is the lack of a criteria for estimating when the Aircraft Vortex Spacing System (AVOSS) will predict the absence of a wake vortex hazard. In previous estimates, we assumed that aircraft spacing can be reduced whenever AVOSS is available. In the current task we examined the practicality of including in the models the vortex advisory system (VAS) wind criteria developed by the FAA. We also investigated how often, and under what meteorological conditions, the VAS criteria would be met at the 10 airports.

This report describes the Chicago models and analysis of the VAS wake vortex criteria as applied to the 10 TAP airports.

Chapter 2

Terminal Area Productivity Airport Wind Analysis

WAKE VORTEX ANALYSIS

The primary purpose of the wake vortex analysis was to develop algorithms that could be used in the capacity and delay models to estimate the impact of the Aircraft Vortex Spacing System (AVOSS). The secondary purpose was to get an initial feel for the potential utility of the AVOSS system at the 10 airports studied.

The analysis is based on the vortex advisory system (VAS) criteria empirically determined by the FAA. The finding of the VAS research was that wake vortices would blow away or decay within 80 seconds when winds are higher than those of an ellipse defined by a head wind semi-major axis of 12 knots and a cross wind semi-major axis of 5.5 knots. When the VAS wind conditions are met, and assuming 135–knot airspeeds, the minimum aircraft spacing can be safely reduced during instrument flight rule (IFR) operations to 3.0 nautical miles for all classes of aircraft.

Applying the VAS criteria to historical weather data is a simple but effective estimating tool. The method has elements of both optimism and conservatism. The optimistic aspect derives from the fact that we assume that the AVOSS system will be able to predict when the VAS criteria will occur. The conservative aspect derives from the fact that AVOSS will be making predictions based on detailed aircraft wake vortex data and, in many cases, will be able to determine that no hazard exists for many specific aircraft pairs, regardless of wind condition.

For our analysis, we constructed a Pascal computer model to read the hourly weather data for the airports and examine whether, and under what conditions, the VAS criteria are satisfied. The model examines the wind conditions for each runway for each hour the airport is open. A “good” condition exists when the winds exceed the VAS ellipse and are within the head wind, cross wind, and tail wind limits. Hourly weather data for 35 years are examined to ensure a statistically representative sample. The results are presented as fractions of the time that good conditions occur.

The algorithms contained in the model procedure Runway Test calculate the VAS wind ellipse and determine whether the winds meet the VAS limits and do not exceed head, tail , and cross wind limit conditions. For each runway, in turn, the program performs the following tasks in order. The program first calculates the relative wind direction over the runway. One of two equations is used depending on the difference between the wind direction and the runway bearing; to wit,

- if wind direction minus runway bearing is positive, then

  relative wind direction = wind direction - runway bearing;

- if wind direction minus runway bearing is negative, then

  relative wind direction = 360 + wind direction - runway bearing.

The program next calculates for each runway, *N*, the polar value of the VAS minimum wind, *VAS*[*N*,*Θ*], in the direction, *Θ*, of the relative wind. With *a* as the head wind component (semi major axis) and *b* as the cross wind component (semi minor axis) the equation is:

$$VAS[N,\Theta] = \frac{a*b}{\sqrt{b^2\cos^2(\Theta) + a^2\sin^2(\Theta)}} \text{, and} \qquad \text{[Eq. 1]}$$

The program next calculates the polar value of the head wind, tail wind and cross wind limit, *HTClimit*, in the direction of the relative wind. In the forward quadrants ($\theta \geq 270$ and $\theta \leq 90$), the limits take the form of an ellipse where the head wind (*HW*) and cross wind (*CW*) limits are the semi-major and semi-minor axes, respectively. In the aft quadrants, we again have an ellipse with the tail wind (*TW*) limit as the semi-major axis. The equations are

for the forward quadrants:

$$HTClimit(N,\Theta) = \frac{HW*CW}{\sqrt{CW^2\cos^2(\Theta) + HW^2\sin^2(\Theta)}}, \qquad \text{[Eq. 2]}$$

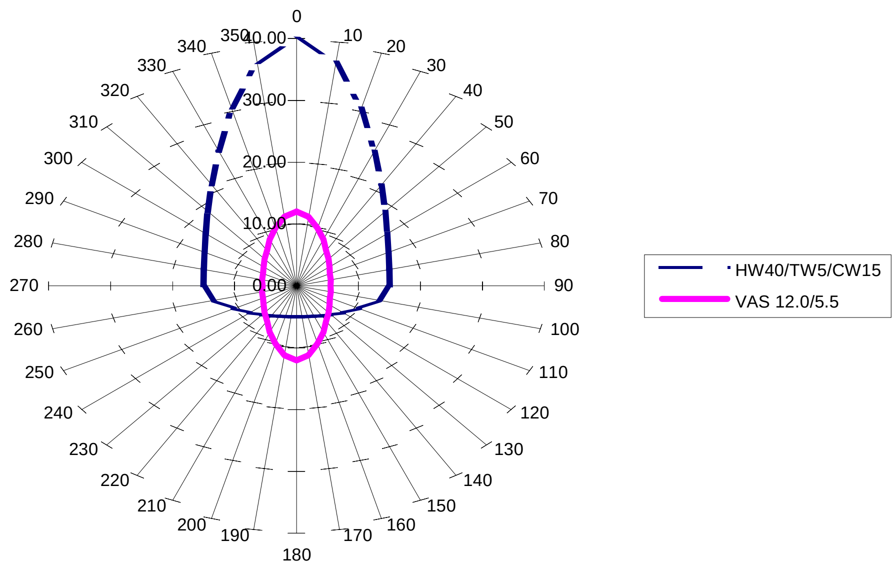
for the aft quadrants:

$$HTClimit(N,\Theta) = \frac{TW*CW}{\sqrt{CW^2\cos^2(\Theta) + TW^2\sin^2(\Theta)}}. \qquad \text{[Eq. 3]}$$

The existing wind is compared with the VAS and HTC limits. The program increments various counters to keep track of the number of cases that satisfy the limits and the conditions under which they occur. A separate procedure calculates fractional frequencies from the raw counts.

Head wind, tail wind, and cross wind (*HTC*) limits of 40, 5, and 15 knots, respectively, were used for all runways. Figure 2-1 shows the basic VAS ellipse and the head wind, cross wind, and tail wind ellipses corresponding to these values.

Figure 2-1. VAS, Head, Tail, and Cross Wind Limits

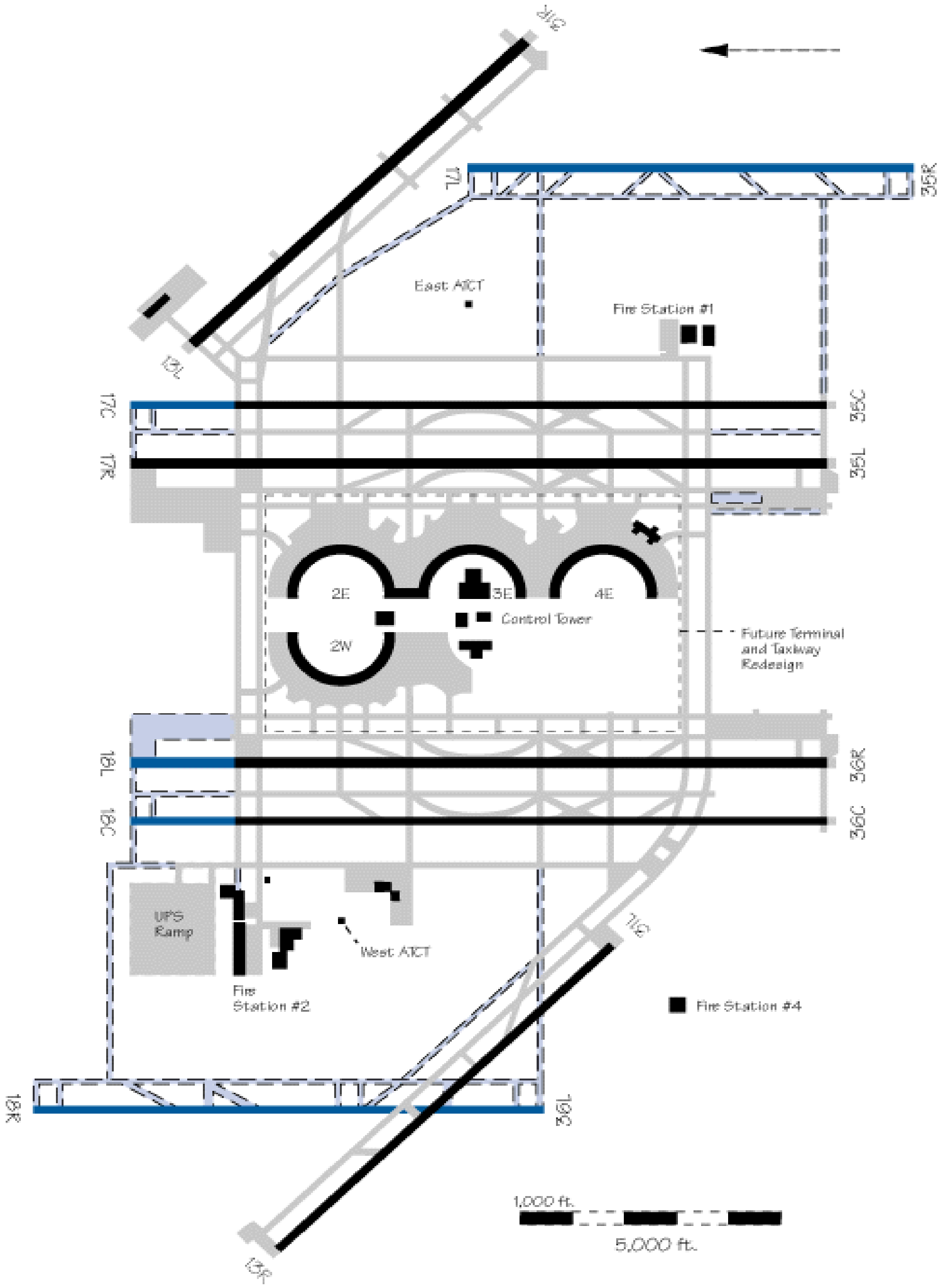


The technical inputs for the model include the runway magnetic bearings for the airport, the airport magnetic declination, and the *HTC* limits. Only one entry is made for parallel runways in each direction. Other inputs include the number of runway cases, a flag to indicate parallel runways, and the distance between centerlines for parallel runways (4,300 feet is used for separations ≥ 4300). Table 2-1 shows the input parameters for the Dallas-Ft. Worth airport (DFW). Note in Table 2-1 that all the north-south runways (17R, 17C, 17L, 18R, 18C, 18L, 35L, 35C, 35R, 36L, 36C, and 36R) are to be represented by cases 18 and 36. Figure 2-2 shows the DFW layout from Reference 1.

Table 2-1. Input Data for DFW

	Name	Code	
Identifiers	Dallas-Ft. Worth	DFW	
Number of runways	4		
Declination	6.4 degrees East		
Runway	Magnetic bearing	Parallel	Separation (feet)
13	132.7	yes	>4,300
31	312.7	yes	>4,300
18	173.8	yes	>4,300
36	353.8	yes	>4,300

Figure 2-2. DFW Layout



Records of 35 years of hourly National Weather Service airport surface weather reports (1961 to 1995) for each airport are used to provide the meteorological data for the analysis. The program includes options for analysis of specific numbers of records and records from specific ranges of dates, but the standard practice is to run all 35 years of data.

The basic data include wind direction and speed, ceiling, visibility, precipitation, and other information. We have augmented the data by identifying the aviation meteorological conditions (instrument meterological conditions [IMC1], IMC2, visual meterological conditions [VMC1], VMC2) based on the specific ceiling and visibility criteria for each airport. We also have flagged any hourly records with missing data. The error-flagged data are not used in the calculations.

The model results include both general and specific measures of VAS conditions. General measures include the fraction of the time at least one runway configuration meets the VAS criteria; frequency of the airport operating conditions (VMC, IMC, etc.); and combinations of the two (e.g., fraction of VMC hours that have at least one good VAS runway). Specific measures include three types of results for specific runways. The first is the fraction of good VAS hours for each runway. The second is the count of good VAS hours as a function of wind bearing for each runway. The third includes fractions of good VAS hours for each runway as functions of aviation meteorological and precipitation conditions (i.e., VMC1 Wet or IMC1 Dry).

Table 2-2 summarizes of the general results for the 10 airports studied. We note from the table that all airports indicate a reasonably high potential for AVOSS effectiveness, but most of the good cases occur in VMC conditions.

Table 2-2. Summary Results of Good VAS Conditions

Airport	Percentage of time VAS conditions at Met		
	All weather	VMC	IMC
Boston (BOS)	90	79	11
New York LaGuardia (LGA)	87	78	9
Newark (EWR)	75	68	8
Detroit (DTW)	74	66	8
San Francisco (SFO)	71	66	5
Dallas-Ft. Worth (DFW)	65	61	4
Atlanta (ATL)	41	36	5
Los Angeles (LAX)	25	22	3
Chicago (ORD)	80	72	8
New York-Kennedy (JFK)	84	75	8

It has been noted in the past that the effective use of VAS criteria may require a preference for cross wind operations. The specific runway results are designed to indicate whether normal airport procedures will need to be changed to take advantage of VAS conditions. The tabulation of good VAS hours as a function of wind-bearing reveals whether a runway's good VAS conditions result from head winds or from cross winds. The fractions of good VAS conditions for specific runways indicates whether the current primary runways are also the primary VAS runways. The best situation is where the primary runways are the top VAS runways and the criteria are primarily met by head winds. Runways 18 and 13 at DFW provide good examples.

Runway 18, representing runways 17R, 17C, 17L, 18R, 18C, and 18L, is the primary south flow DFW configuration. Runway 13, representing 13L and 13R, are auxiliary runways. Runway 18 meets the VAS criteria 34 percent of the time, while Runway 13 meets the criteria 39 percent of the time. Figure 2-3 shows the fraction of good counts for Runway 18 as a function of wind direction. It is clear from the figure that good VAS conditions for Runway 18 occur in normal head wind operations.

Figure 2-3. Runway 18 Counts Versus Direction

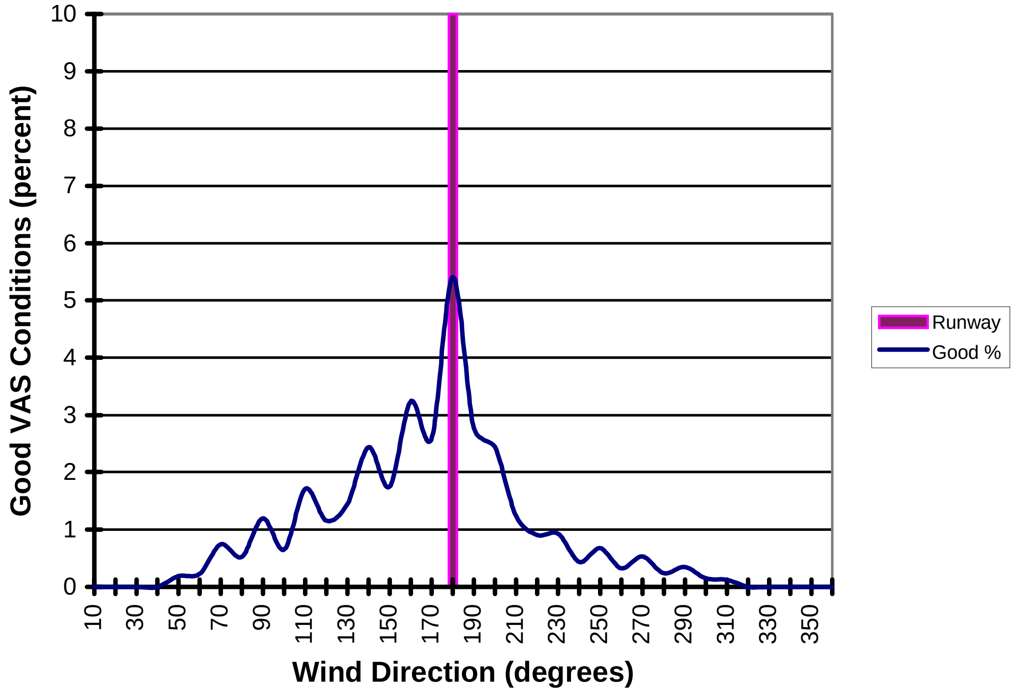
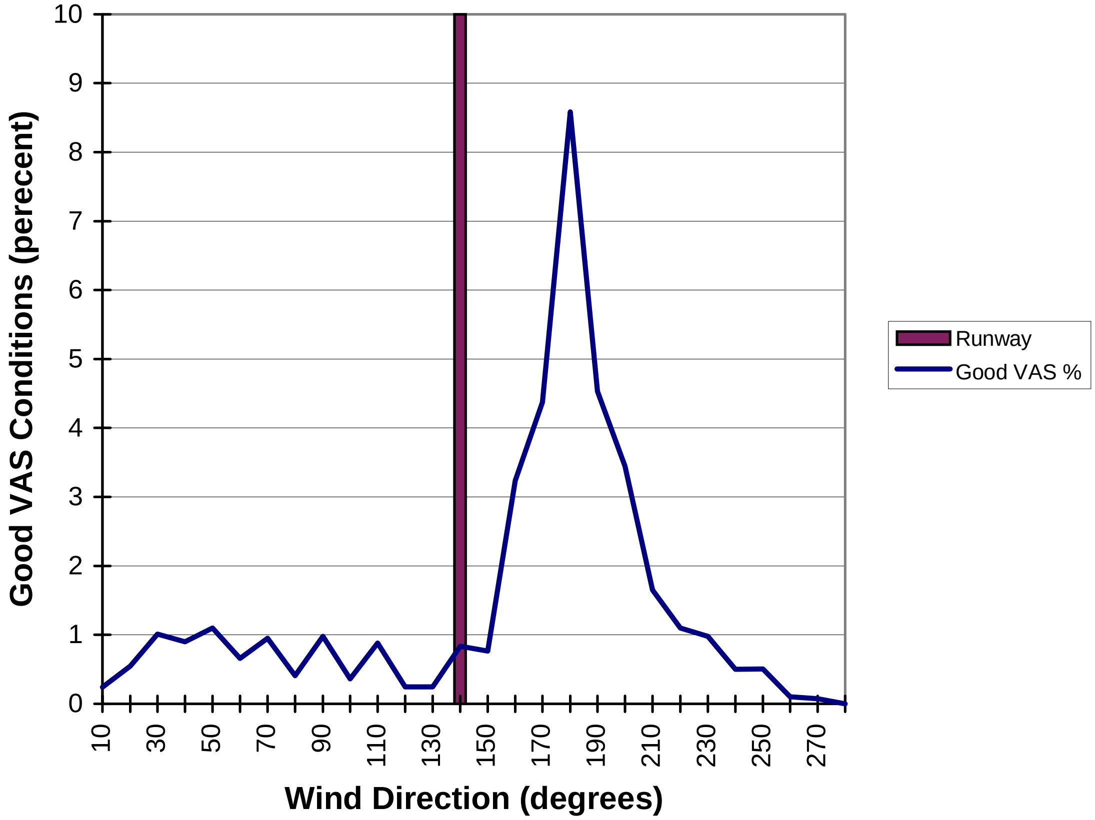


Figure 2-4 shows the same data for runway 13. In this case, the good VAS conditions are due mostly to cross winds. Since both figures indicate that good VAS conditions are due to winds from the same bearing, we can reason that both sets of runways will have good VAS conditions at the same time.

The final set of specific runway data addresses the meteorological conditions that correspond to good VAS conditions. This information is useful for determining what other TAP technologies may be needed to realize the benefits of AVOSS. For example, if the bulk of the good VAS conditions occur under IMC-2 wet conditions, then both taxi-navigation and situation awareness (T-NASA) and roll-out and turn-off (ROTO) technologies probably will be required to gain the full benefit of AVOSS. On the other hand, if most of the good VAS conditions occur during VMC-1, then we must address how AVOSS information can benefit not only the controller but also the pilots who, in VMC-1 are responsible for safe separation. Again, we use DFW as the example.

Figure 2-4. Runway 13 Counts Versus Direction



As reported in Table 2-2, at least one runway at DFW meets the VAS conditions 65 percent of the time. When the results are broken down by specific runways we find the following:

Runway	Good VAS Conditions
13	39%
31	26%
18	34%
36	22%

These results can be further broken down to examine the meteorological conditions that exist when the VAS conditions are met. Table 2-3 contains such a breakout reported in relative percentage (adding to 100 percent for the airport). Table 2-4 contains the same breakout reported in absolute percentages (adding to the good VAS condition percentage for the runway).

Table 2-3. Relative Percentage of Good VAS Conditions for Specific Runways at DFW as a Function of Meteorological Conditions

Meteorological conditions	Runway 13 (%)	Runway 31 (%)	Runway 18 (%)	Runway 36 (%)
VMC-1 dry	81	75	80	72
VMC-2 dry	11	13	12	14
IMC-1 dry	1	2	1	2
IMC-2 dry	0	0	0	0
VMC-1 wet	2	2	2	2
VMC-2 wet	2	3	2	4
IMC-1 wet	3	5	3	6
IMC-2 wet	0	1	0	1
Totals	100	101*	100	101*

*Total > 100 due to round-off errors.

Table 2-4. Absolute Percentage of Good VAS Conditions for Specific Runways at DFW as a Function of Meteorological Conditions

Meteorological conditions	Runway 13 (%)	Runway 31 (%)	Runway 18 (%)	Runway 36 (%)
VMC-1 dry	31.6	19.2	27.5	16.0
VMC-2 dry	4.2	3.3	4.0	3.0
IMC-1 dry	0.4	0.4	0.3	0.4
IMC-2 dry	0	0	0	0
VMC-1 wet	0.9	0.6	0.7	0.6
VMC-2 wet	0.8	0.8	0.7	0.8
IMC-1 wet	1.2	1.3	1.0	1.3
IMC-2 wet	0.2	0.1	0.1	0.1
Totals	39.3	25.7	34.3	22.2

The results indicate that good VAS conditions at DFW do indeed occur primarily during VMC conditions for all runways.

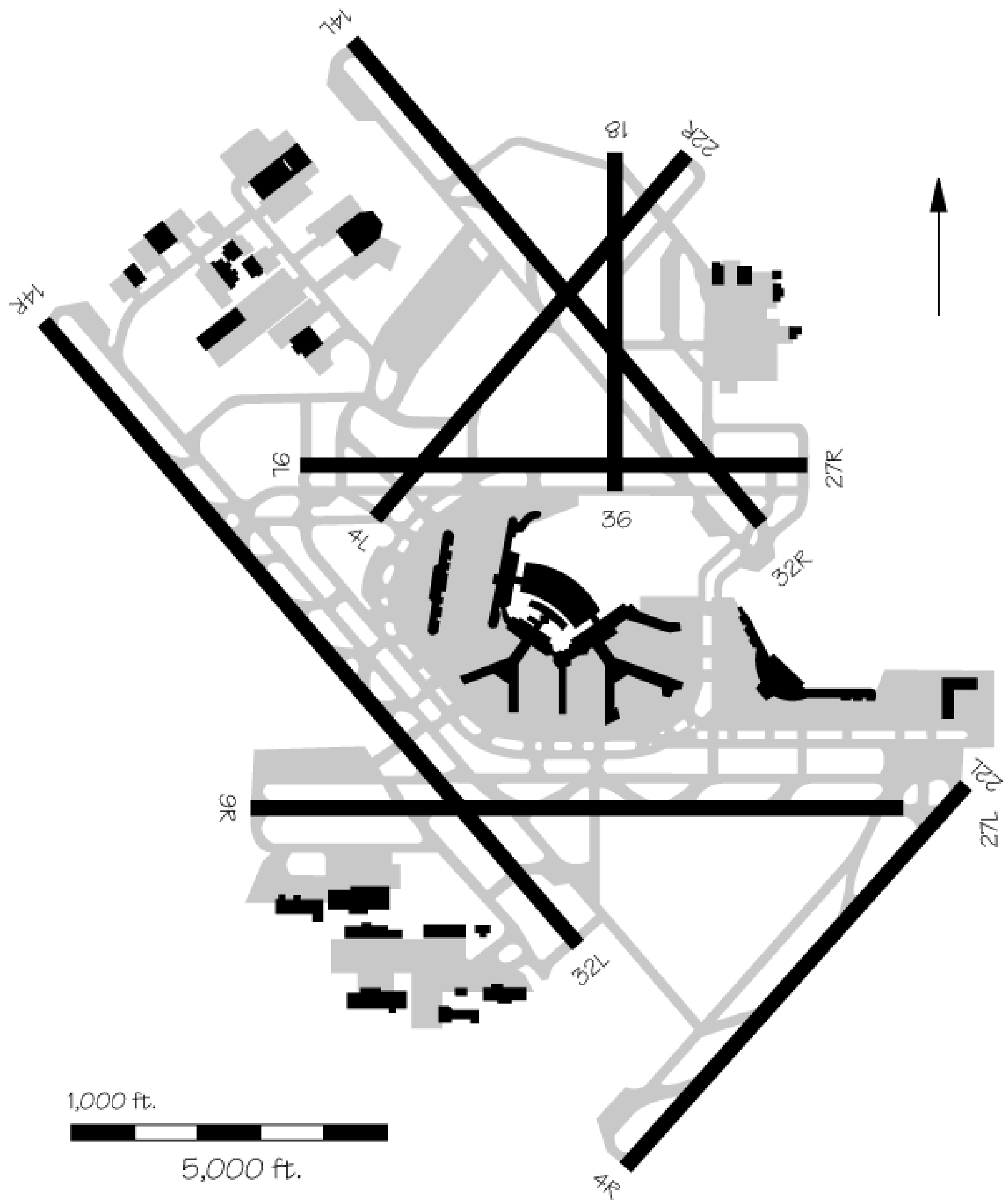
SUMMARY

Results have been obtained for all 10 airports. The computer model and all the airport and weather data have been provided to NASA. The analyses performed have successfully checked out the algorithms to be used in the airport capacity models and have in the process provided insight into the potential utility of AVOSS.

Chapter 3
Chicago Airport Model

This section describes the unique aspects of the capacity and delay models for the Chicago O'Hare airport (ORD). Our basic modeling approach and algorithms are described in Reference 2. The specific configurations of ORD, unique modeling considerations, and summaries of results are presented below. Figure 3-1 is a layout of ORD taken from Reference 1.

Figure 3-1. ORD Diagram



RUNWAY CONFIGURATIONS

The Chicago O'Hare airport has seven operational runways and three types of configurations: triple approaches, dual approaches, and parallel approaches. A departure–only approach is also modeled for those rare cases when the airport is below ILS minima for arrivals but still open for departures.

The triple approaches are only legal in VMC conditions. Those configurations allow three (or more) arrival runways to be used simultaneously with converging approaches. The triple approaches are known as "Plan B Trip 22," "Plan B Trip 27," "Plan X," "Plan Weird Trip 27," and "Parallel 27 Trip 32."

The dual-approach configurations have two arrival runways with converging approaches. These configurations are legal if the ceiling is above 700 feet and visibility is over 2 miles. The dual approach plans are known as "Plan B," "Modified Plan X," and "Plan Weird."

The parallel approaches use two parallel runways. There are five versions of parallel 9s, and six versions of parallel 14s, depending on which departure runways are available. There are also parallel 22, parallel 27, and parallel 32 configurations. Parallel 4 is not used.

The configurations and their runways are listed in Table 3-1. The usage of each runway in the configuration is indicated as follows:

- A: arrival only for any type of aircraft
- AT: turboprop arrivals
- AX: any arrivals except heavy jets
- D: departures only
- M: mixed operations—arrival and departures.

Table 3-1. ORD Runway Configurations

Configuration	Runway											
	4L	4R	9L	9R	14L	14R	22L	22R	27L	27R	32L	32R
Depart only	Not modelled; assume two in use											
Plan B Trip 22					AT	A	M	A	D			
Plan B Trip 27					AT	A	D	A	D	AX		
Parallel 27 Trip 32L							D		A	A	M	D
Plan X	D	A	M	A							D	D
Plan Weird Trip 27							D	A	A	AX	D	

Table 3-1. ORD Runway Configurations (Continued)

Configuration	Runway											
	4L	4R	9L	9R	14L	14R	22L	22R	27L	27R	32L	32R
Plan B						A	D	A	D			
Plan Weird							D	A	A		D	
27s							D		A	A	D	D
Mod Plan X	D	A	A	D								D
9s depart 4L 22L	D		A	M			D					
9s depart 32R 22L			A	M			D					D
9s depart 22L			A	M			D					
9s depart 4L	D		A	M								
9s depart 32R			A	M								D
14s			D		A	A	D		D			
14s no depart 27			D		A	A	D					
p14 no depart 9	D				A	A	D		D			
p14 no depart 9 or 4					A	A	D		D			
p14 no depart 22			D		A	A			D			
p14 depart 9s			D	D	A	A						
32s									D		M	M
22s							M	M	D	D		

MODEL OPERATION

The meteorological conditions for ORD are defined as follows:

Condition	Ceiling in feet	Visibility in miles
VMC-1	>4,500	>7
VMC-2	>1,000	>3
IMC-1	>700	>2
IMC-2	all other	all other

If we are in VMC-1 or VMC-2, some triple configuration is chosen, if any is available, given the winds. If the weather in the previous hour was IMC-1, the triple associated with the dual configuration that was in use is chosen, if it is available. For example, Parallel 27 Triple 32 is chosen if parallel 27 previously was in use; the highest capacity version of the Plan B triples is chosen if Plan B was in use. If no dual was in use, or its associated triple is not available, then the highest capacity usable configuration is chosen.

If the weather is IMC-1, we check to see if we were in a triple configuration the previous hour. If so, then the dual configuration associated with the triple is used if it is available. Otherwise, the highest capacity available configuration is chosen.

After being in departure only or at the beginning of the day, the highest capacity usable configuration is chosen.

We do not model configuration shifts that are not induced by weather, such as rotating configurations to spread noise impact.

RESULTS

Tables 3-2, 3-3, 3-4, and 3-5 show the balanced operations capacities of each airport configuration, as well as departure emphasis and arrival emphasis capacities where appropriate. The four tables correspond to the four meteorological conditions. The capacities are reported per hour based on the 1993 OAG aircraft type mix.

Table 3-2. ORD VMC-1 Capacity

Configuration	Balanced		Arrival heavy		Departure heavy	
	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity
Plan B Trip 22	121	105	160	72		
Plan B Trip 27	150	106				
Parallel 27 Trip 32L	111	111	119	98	79	132
Plan X	98	92	105	70	79	158
Plan Weird Trip 27	108	106				
Plan B	79	106				
Plan Weird	79	106				
27s	79	132				
Mod Plan X	79	92				
9s depart 4L 22L	79	111			40	145
9s depart 32R 22L	79	111			40	145
9s depart 22L	79	72			40	106
9s depart 4L	71	71	79	59	40	93
P9s depart 32R	71	71	79	59	40	93
14s	71	137				
14s no depart 27	71	84				
p14 no depart 9	71	137				
p14 no depart 9 or 4	79	106				
p14 no depart 22	71	84				
p14 depart 9s	71	84				
32s	71	71	79	40	40	93
22s	71	71				

Table 3-3. ORD VMC-2 Capacity

Configuration	Balanced		Arrival heavy		Departure heavy	
	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity
Plan B Trip 22	106	102	141	73		
Plan B Trip 27	134	102				
Parallel 27 Trip 32L	100	100	105	92	70	121
Plan X	88	90	95	73	70	153
Plan Weird Trip 27	97	102				
Plan B	70	102				
Plan Weird	70	102				
27s	70	121				
Mod Plan X	70	86				
9s depart 4L 22L	70	108			35	137
9s depart 32R 22L	70	108			35	137
9s depart 22L	70	73			35	102
9s depart 4L	65	65	70	57	35	86
9s depart 32R	65	65	70	57	35	86
14s	65	132				
14s no depart 27	65	81				
p14 no depart 9	65	132				
p14 no depart 9 or 4	70	102				
p14 no depart 22	65	81				
p14 depart 9s	65	81				
32s	65	65	70	35	35	86
22s	65	65				

Table 3-4. ORD IMC-1 Capacity

Configuration	Balanced		Arrival heavy		Departure heavy	
	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity
Plan B Trip 22						
Plan B Trip 27						
Parallel 27 Trip 32L						
Plan X						
Plan Weird Trip 27						
Plan B	70	100				
Plan Weird	70	100				
27s	70	120				
Mod Plan X	70	86				
9s depart 4L 22L	70	105			35	136
9s depart 32R 22L	70	105			35	136
9s depart 22L	70	70			35	100
9s depart 4L	64	64	70	54	35	86
9s depart 32R	64	64	70	54	35	86
14s	64	130				
14s no depart 27	64	80				
p14 no depart 9	64	130				
p14 no depart 9 or 4	70	101				
p14 no depart 22	64	80				
p14 depart 9s	64	80				
32s	64	64	70	35	35	86
22s	64	64				

Table 3-5. ORD IMC-2 Capacity

Configuration	Balanced		Arrival heavy		Departure heavy	
	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity	Arrival capacity	Departure capacity
Plan B Trip 22						
Plan B Trip 27						
Parallel 27 Trip 32L						
Plan X						
Plan Weird Trip 27						
Plan B						
Plan Weird						
27s						
Mod Plan X						
9s depart 4L 22L	64	79			32	123
9s depart 32R 22L	64	79			32	123
9s depart 22L	64	47			32	91
9s depart 4L	53	53	64	34	32	77
9s depart 32R	53	53	64	34	32	77
14s	53	112				
14s no depart 27	53	67				
p14 no depart 9	53	112				
p14 no depart 9 or 4	64	91				
p14 no depart 22	53	67				
p14 depart 9s	53	67				
32s	53	53	64	32	32	77
22s	53	53				

Table 3-6 shows the configurations chosen by the model for ORD, during normal operating hours (5 a.m. to 2 a.m. local time). The weather data are the same 35-year historical data set used in the wake vortex analysis. For those hours where there was missing weather data, no observation is recorded. Both the total counts and the percentage of total operations are shown. The configurations are further segregated by weather conditions.

Table 3-6. ORD Estimated Runway Configuration Use

	VMC-1		VMC-2		IMC-1		IMC-2		ALL WX
Configuration	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Percent
Depart Only	0	0.00	0	0.00	0	0.00	594	0.23	0.23
Plan B Trip 22	6,685	2.60	6,633	2.58	0	0.00	0	0.00	5.18
Plan B Trip 27	36,989	14.39	19,193	7.47	0	0.00	0	0.00	21.85
Parallel 27 Trip 32L	45,615	17.74	13,354	5.19	0	0.00	0	0.00	22.94
Plan X	61,610	23.96	23,874	9.29	0	0.00	0	0.00	33.25
Plan Weird Trip 27	4,127	1.61	4,623	1.80	0	0.00	0	0.00	3.40
Plan B	0	0.00	0	0.00	2,055	0.80	0	0.00	0.80
Plan Weird	0	0.00	0	0.00	353	0.14	0	0.00	0.14
27s	204	0.08	238	0.09	3,113	1.21	6,572	2.56	3.94
Mod Plan X	731	0.28	530	0.21	2,983	1.16	0	0.00	1.65
9s depart 4L 22L	641	0.25	512	0.20	511	0.20	1,666	0.65	1.30
9s depart 32R 22L	0	0.00	0	0.00	21	0.01	30	0.01	0.02
9s depart 22L	0	0.00	0	0.00	0	0.00	0	0.00	0.00
9s depart 4L	40	0.02	65	0.03	281	0.11	1,253	0.49	0.64
9s depart 32R	0	0.00	0	0.00	0	0.00	0	0.00	0.00
14s	126	0.05	117	0.05	507	0.20	1,408	0.55	0.84
14s no depart 27	40	0.02	38	0.01	4	0.00	33	0.01	0.04
p14 no depart 9	0	0.00	0	0.00	18	0.01	20	0.01	0.01
p14 no depart 9 or 4	0	0.00	0	0.00	96	0.04	1,003	0.39	0.43
p14 no depart 22	142	0.06	142	0.06	282	0.11	1,339	0.52	0.74
p14 depart 9s	26	0.01	45	0.02	232	0.09	1,180	0.46	0.58
32s	899	0.35	1,227	0.48	412	0.16	482	0.19	1.17
22s	1,423	0.55	580	0.23	112	0.04	73	0.03	0.85
Total counts	159,298		71,171		10,980		15,653		
Percent time in MC	61.96		27.68		4.27		6.09		100.00

Table 3-7 shows the estimated 1997 average arrival and departure delay for each runway configuration and meteorological condition, using the 1993 OAG demand data for a typical weekday inflated by 6 percent based on the FAA terminal area forecast. Delay is reported in minutes per flight.

Table 3-7. ORD Estimated Delays per Configuration (in Minutes)

Configuraton	VMC1		VMC2		IMC1		IMC2	
	Arrival delay	Departure delay	Arrival delay	Departure delay	Arrival delay	Departure delay	Arrival delay	Departure delay
Plan B Trip 22	3.7	3.7	3.8	4.1	N/A	N/A	N/A	N/A
Plan B Trip 27	3.8	3.7	3.8	4.3	N/A	N/A	N/A	N/A
Parallel 27 Trip 32L	3.3	2.9	4.5	3.2	N/A	N/A	N/A	N/A
Plan X	4.1	3.6	6.5	4.6	N/A	N/A	N/A	N/A
Plan Weird Trip 27	4.9	3.7	6.7	4.3	N/A	N/A	N/A	N/A
Plan B	17.2	3.7	54.0	4.3	54.1	4.4	N/A	N/A
Plan Weird	17.2	3.7	54.0	4.3	54.1	4.4	N/A	N/A
27s	17.3	3.0	54.2	3.1	54.1	3.2	99.2	3.5
Mod Plan X	17.6	5.3	54.4	8.3	54.4	8.6	N/A	N/A
9s depart 4L 22L	17.4	3.4	55.0	3.6	55.1	3.7	99.2	16.4
9s depart 32R 22L	17.4	3.4	55.0	3.6	55.1	3.7	99.2	16.4
9s depart 22L	26.0	20.1	56.2	32.4	59.7	44.1	152.4	149.0
9s depart 4L	51.8	50.5	94.0	91.7	100.6	98.2	208.3	204.2
9s depart 32R	51.8	50.5	94.0	91.7	100.6	98.2	208.3	204.2
14s	46.7	3.0	88.5	3.0	95.3	3.0	205.0	3.3
14s no depart 27	46.3	9.5	88.4	13.4	95.3	15.4	206.3	79.5
p14 no depart 9	46.7	3.0	88.5	3.0	95.3	3.0	205.0	3.3
p14 no depart 9 or 4	17.2	3.7	54.0	4.3	54.1	4.4	99.5	5.9
p14 no depart 22	46.3	9.5	88.4	13.4	95.3	15.4	206.3	79.5
p14 depart 9s	46.3	9.5	88.4	13.4	95.3	15.4	206.3	79.5
32s	56.9	55.1	99.4	96.9	105.3	102.5	208.7	204.7
22s	61.9	47.0	106.5	91.2	113.5	98.3	230.7	216.1

We close the discussion of the ORD capacity and delay models by comparing the annual delay results estimated by the detailed model with those estimated by the LMINET delay model used in Reference 3. For the 2005 baseline inputs used in Reference 3 and using the 2005 demand level, the detailed model predicts 5.98 million annual minutes of arrival delay (averaged over 35 years of weather data). The result for 2005 in Reference 3 was 3.41 million annual minutes of arrival delay. The difference is significant. Part of the difference is due to the fact that the LMINET calculations only use 1995 weather. The detailed model result for 1995 weather only is 4.91 million minutes. Much of the remaining disparity is due to the different queuing engines used in the models.

The LMINET model used for Reference 3 contained a "fluid flow" queuing engine. The detailed model uses an M/M/1 queuing engine with the Rothkopf-Orem closure hypothesis. The fluid flow engine only predicts delays when demand exceeds capacity, while the M/M/1 engine more accurately predicts the formation of a queue when operations approach capacity from below. The fluid flow and M/M/1 engines give similar results when demands alternate from well below capacity to well above capacity. In such cases the fluid flow engine is preferred because of its computational efficiency. In a case like ORD, where demand often hovers near capacity, the results of the two engines are expected to be different. During the past year the LMINET models have been equipped with the M/M/1 queuing engine. The result for the 2005 baseline using LMINET and the M/M/1 engine is 4.43 million annual minutes of arrival delay.

The degree of agreement between the arrival delay results for the detailed model using 1995 weather data (4.91 million minutes) and the LMINET model using the M/M/1 queuing engine and 1995 weather data (4.43 million minutes) is encouraging. The results indicate that the LMINET reasonably approximates the detailed results, but that adding detail does make a measurable improvement in the estimate.

References

1. *FAA 1996 Aviation Capability Enhancement Plan and Airport Data Base*, 1996.

2. David Lee, et. al., *Estimating the Effects of the Terminal Area Productivity Program*, NASA Contractor Report 201682, April 1997.

3. *Preliminary Cost-Benefit Estimates of Terminal Area Productivity Program Technologies,* Hemm, Shapiro, Nelson, and Lee, LMI Report Number LMI-NS604S1, NASA Contractor Report to be published, September 1997.

Appendix A
Airport Identifiers

ATL	The William B. Hartsfield Atlanta International Airport, Atlanta, Georgia
BOS	General Edward Lawrence Logan International Airport, Boston, Massachusetts
DFW	Dallas-Fort Worth International Airport, Dallas/Fort Worth, Texas
DTW	Detroit Metropolitan Wayne County Airport, Detroit, Michigan
EWR	Newark International Airport, Newark, Ohio
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport, Los Angeles, California
LGA	La Guardia Airport, New York, New York
ORD	Chicago O'Hare International Airport
SFO	San Francisco International Airport, San Francisco, California

Appendix B

Abbreviations

AILS	Airborne Information for Lateral Spacing
AT	Turboprop Arrivals
AVOSS	Airborne Information for Lateral Spacing
AX	Any arrivals except heavy jets
CW	Cross-wind
FAA	Federal Aviation Administration
HTC	Head, tail, cross wind
HTClimit	Head, tail, cross wind limit
HW	Head wind
IFR	instrument flight rule
ILS	Instrument Landing System
IMC	instrument meterological conditions
LMINET	A queuing network model of the U.S. national airspace system
MC	meterological conditions
NASA	National Aeronautics and Space Administration
OAG	Official Airline Guide
ROTO	roll-out and turn-off
TAP	Terminal Area Productivity Program
T-NASA	Taxi-navigation and situation awareness
TW	Tail wind
VAS	Vortex Advisory System
VMC	visual meterological conditions

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This paper describes two results from a continuing effort to provide accurate cost-benefit analyses of the NASA Terminal Area Productivity (TAP) program technologies. Previous tasks have developed airport capacity and delay models and completed preliminary cost benefit estimates for TAP technologies at 10 U.S. airports. This task covers two improvements to the capacity and delay models. The first improvement is the completion of a detailed model set for the Chicago O'Hare (ORD) airport. Previous analyses used a more general model to estimate the benefits for ORD. This paper contains a description of the model details with results corresponding to current conditions.

The second improvement is the development of specific wind speed and direction criteria for use in the delay models to predict when the Aircraft Vortex Spacing System (AVOSS) will allow use of reduced landing separations. This paper includes a description of the criteria and an estimate of AVOSS utility for 10 airports based on analysis of 35 years of weather data.

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