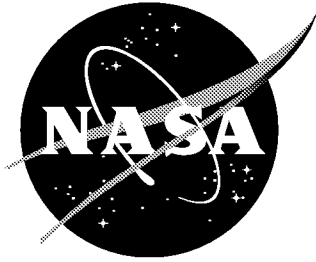NASA/TM-2000-209849

An Initial Study of the Sensitivity of Aircraft Vortex Spacing System (AVOSS) Spacing Sensitivity to Weather and Configuration Input Parameters

Stephen E. Riddick and David A. Hinton
Langley Research Center, Hampton, Virginia

January 2000

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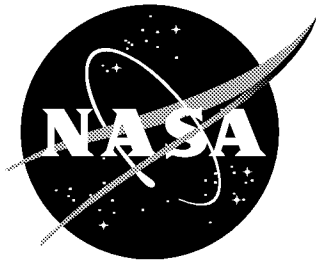- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

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ABSTRACT

A study has been performed on a computer code modeling an aircraft wake vortex spacing system during final approach. This code represents an initial engineering model of a system to calculate reduced approach separation criteria needed to increase airport productivity. This report evaluates model sensitivity toward various weather conditions (crosswind, crosswind variance, turbulent kinetic energy (TKE), and thermal gradient), code configurations (approach corridor option, and wake demise definition), and post-processing techniques (rounding of provided spacing values, and controller time variance).

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is sponsoring development of technologies which will increase the productivity of airports during Instrument Meteorological Conditions (IMC). The technology that this report will investigate is the Aircraft VOrtex Spacing System (AVOSS), developed under the Terminal Area Productivity (TAP) program. The AVOSS is intended to predict air traffic spacing needed to ensure an approaching aircraft's wake does not affect the next aircraft in the pattern.

Small	Large	Heavy
<41,000 lb.	41,000 – 255,000 lb.	>255,000 lb.

Table 1 – Aircraft classifications by Maximum Takeoff Gross Weight.

Following Aircraft	Leading (Generating) Aircraft			
	Small	Large	B757	Heavy
Small	3*	4	5	6
Large	3*	3*	4	5
Heavy	3*	3*	4	4

* 2.5 for < 50 second runway occupancy time (ROT)

Table 2 – FAA threshold spacing criteria (NM).

The spacing criteria currently used by the FAA is dependent on aircraft weight categories (table 1) and specifies the spacing values shown in table 2. These values are based on worst-case wake behavior and are used in all weather conditions, creating inefficiencies when the weather is acting to rapidly decay or move wakes from the approach corridor. AVOSS is a weather-dependent system. It analyzes the meteorological conditions in the vicinity of the approach corridor and predicts the time required for the aircraft wake to decay or transport out of the approach path. Using the approach velocities of the following and leading aircraft, it then calculates the spacing needed between the aircraft to ensure each plane's wake is no longer a safety concern for the following aircraft. Previous studies indicate AVOSS has the potential to increase runway throughput by an average of 9%[1].

ABBREVIATIONS

ATC – Air Traffic Control

AVOSS – Aircraft VOrtex Spacing System

CTAS – Center-TRACON Automation System

DFW – Dallas/Fort Worth International Airport

EDR – Eddy Dissipation Rate (m^2/s^3)

FAA – Federal Aviation Administration

IMC – Instrument Meteorological Conditions

MGLW – Maximum Gross Landing Weight

NASA – National Aeronautics and Space Administration

NM – Nautical Mile

RMS - Root-Mean-Square

ROT – Runway Occupancy Time

TAP – Terminal Area Productivity Program

TKE – Turbulent Kinetic Energy (m^2/s^2)

PURPOSE OF STUDY

The purpose of this study is to analyze the effects of various weather conditions and configuration options on AVOSS performance. This information will aid developers of the AVOSS technology to better understand the effect of various weather variables on system performance. This investigation is also a tradeoff study between system options, post-processing choices, and system performance. The information gained from this experiment should prove useful for the refinement of the current code for a prototype system demonstration.

AVOSS CONFIGURATION

The NASA Terminal Area Productivity program is developing the AVOSS technology for concept demonstration, with a live system operating in real time in an operational airport environment. The demonstration will take place in the year 2000 at the Dallas-Fort Worth International airport. The AVOSS spacing values will not be provided to the actual Air Traffic Control (ATC) system during this demonstration and no actual aircraft will receive altered spacing. The AVOSS is undergoing an iterative system development process involving improvements in the weather system, wake prediction algorithms, and wake detection systems. This study is evaluating the first integrated system as an aid to focusing development of the demonstration system. AVOSS software Version 1.70 was used in this study and the results are intended to aid development of Version 2 for the final project demonstration.

The current AVOSS system reads observed weather data, provides this data to a wake predictor algorithm, and provides aircraft separation values required to avoid wake encounters. Spacing values are provided for the runway threshold, at various points along the approach, and at the top of the approach. The top-of-approach value, if met, will provide safe wake separation at all locations on final given expected aircraft speeds and distance compression on final. Post processing is applied to estimate the effects of an ATC interface on system performance. No actual ATC interface exists in this version of AVOSS. Future versions will also use data from wake detectors to validate the wake predictions and monitor safety.

The incoming weather data represents a 30-minute average of the relevant weather parameters, with confidence intervals for crosswind. Based on this information, AVOSS computes the potential wake drift and decay times for the wake vortices of each landing aircraft type over the next 30 minutes, assuming persistence of the weather statistics. The use of statistical weather data is intended to provide adequate stability to the output for practical use by ATC in establishing final approach spacing.

Approach Safety Corridor

The approach safety corridor is the section of airspace where wake presence is considered potentially hazardous to landing operations. The dimensions of the approaching aircraft and the uncertainty of its position (flight technical error) on the approach are considered in the definition of the safety corridor[2]. The corridor is centered along the localizer and consists of a specified lateral area to each side of the localizer, and a specified distance below the 3-degree glide slope. The lower boundary of the corridor is referred to as the corridor floor. There is no upper boundary to the corridor. A series of locations along the approach, referred to as windows, are used to predict wake motion and decay. The approach corridor dimensions at the windows used in this study are shown in table 3 and defined by equations found in reference 1.

The vertical dimension of the safety corridor is used to determine when a wake is safely below the expected flight path of following aircraft. Along the runway and out to a "transition point", where the glide slope is about 61 meters (200 feet) above the ground, the corridor floor is at ground level. At distances from the runway greater than the transition point, the corridor floor transitions from ground level to a distance below glideslope. Two corridor floor options are implemented beyond the transition point. Option 1, the more conservative definition, defines the corridor floor to be at ground level at the transition point sloping linearly to 136 meters (446 ft.) below the glide slope at the glide slope intercept. Option 2 defines a step function in floor height from ground level at the transition point to 21.3 meters (70 ft.) below glide slope just beyond the

Distance from Threshold (m)	Glide Slope Height Above Runway (m)	Altitude of Corridor Floor (Option 1) (m)	Altitude of Corridor Floor (Option 2) (m)	Width of Safety Corridor (m)
0	17	0	0	91.5
430	39	0	0	91.5
843	61	0	0	91.5
982	68	6	46	95
5000	279	188	238	197
11128	600	464	530	352 or 20000*

*20 km width at outer window disables wake lateral motion from reducing aircraft spacing, for uncertainty of aircraft lateral position while intercepting the localizer. The 352 meter width is used to enable use of wake lateral drift.

Table 3 – Approach corridor dimensions at each window. (meters)

transition point. The floor then slopes linearly to 70 meters (300 ft.) below the glide slope at the glide slope intercept point. Since wakes tend to not sink below about 1/2 span of the generating aircraft, about 30.5 meters (100 ft.) for a B-747, no spacing benefit is gained from regions where the corridor floor is less than about 30 meters above ground, hence the step floor height.

The lateral dimension of the safety corridor is held constant along the runway and out to the transition point. In this example, the transition point is 843 meters from the threshold. Beyond this point the corridor widens to accommodate less precise navigation performance farther from the runway. At the glide path intercept location, the corridor abruptly widens to 20 km. The purpose of this increase is to prevent reduced spacing due to wake lateral drift at that altitude. This feature is a first approximation to a technique to allow the spacing specified at the glide slope intercept altitude to also be used as aircraft intercept the localizer farther out, since the spacing is governed only by demise and wake sink rate at that altitude.

The safety corridor is used to compute wake vortex "residence time" at each window. The residence time is defined as the minimum of the wake vortex "transport time" or the "demise time" at each window. The transport time is the time required for the wakes to either drift laterally out of the corridor or sink below the corridor floor. Since the corridor floor is at ground level near the runway, spacing reduction can never be provided due to wake vertical motion in that regime. Demise time is based on a wake demise definition. This term refers to a circulation strength value at which the aircraft wake has decayed and has become indistinguishable from surrounding turbulence. The length of time required to decay to this threshold is computed and used as the demise time. Since small aircraft can be affected by wakes that are too weak for reliable detection by current wake sensors, AVOSS presently does not use the demise factor when calculating the required following distance for small aircraft behind other aircraft. Small aircraft spacing can only be reduced when the wake is forecast to exit the safety corridor. As will be seen, this feature leads to non-intuitive relations between small aircraft spacing and many other system parameters.

Approach Spacing Definition

All spacing values to be discussed in this report are the required distance between aircraft at the top of the approach, or the glide slope intercept point, required to meet all wake vortex constraints between the glide slope intercept and the runway threshold. The location of the top-of-approach is referred to as the "spacing point". This value is referred to as the "approach" spacing value. Use of approach spacing, rather than threshold spacing, is needed to assess the actual benefits of wake systems, since it is possible to find conditions that may improve spacing at one location on the approach, while a different location is constraining operations. Use of the approach spacing allows a system-level assessment of performance.

Approach spacing is calculated by first determining the spacing required, in terms of time, at the series of windows defined in table 3. This spacing interval is referred to as the "window" spacing requirement. The residence time values discussed above form the spacing requirement at each window. For each window spacing time, an adjusted time is computed that would be required at the spacing point to meet the window spacing requirement, based on the expected airspeed of the generator and follower aircraft and the head wind along the approach. For example, if 70 seconds of spacing is required at the threshold, the generator is expected to have an average ground speed of 60 m/s, the follower is expected to have an average ground speed of 75 m/s, and the distance from the spacing point to the runway is 11000 meters, then 106.7 seconds of spacing are required at the spacing point. For each aircraft pair the adjusted time is computed for all windows, and the largest of these is taken as the actual approach spacing required. Since the current AVOSS output is given for aircraft weight categories, the time adjustment is performed for each generator aircraft type and the maximum speed of the follower category, and the worst case time chosen for that generator category. Hence the worst case generator within a weight category will set the spacing required behind all other aircraft in that category. For output the time-based spacing at each window and for the approach is converted to distance, using the ground speed of the follower aircraft.

Two limits are applied to the wake spacing values. A minimum spacing is prescribed at the runway threshold for Runway Occupancy Time (ROT) considerations. That value is set to 2.5 NM in this study. Secondly, the spacing criteria required under current regulations are applied as maximum spacing values at each approach window. These values are used when weather uncertainties or other factors prevent reliable wake prediction.

AVOSS Inputs

The AVOSS code reads six input files in batch mode. The turbulence file, the wind file, and the thermal file describe the weather conditions around the airport. The

parameter file, the aircraft database, and the default spacing matrix file are used to configure the AVOSS system operation.

The three weather files provide the atmospheric profile from altitudes at the surface to the glide slope intercept. This data is used to compute vortex transport and decay behavior. The turbulence file contains wind RMS velocity values (square root of twice the TKE value). This file specifies the atmospheric turbulence above the airport. The wind file contains the atmospheric wind profile and supplies values for mean crosswind, mean headwind, crosswind variance, headwind variance, and vertical shear. The thermal input file provides a column estimate of air temperature above the airport. The current configuration uses a 30-minute statistic of the weather variables.

The parameter file selects configuration settings for the AVOSS system. Examples include the corridor option number and the wake demise definition.

The aircraft database describes the aircraft for which wake predictions will be made. A cross section of aircraft in each weight category is included, with emphasis on the types expected at the airport and selection of worst-case wake aircraft in each category. This file currently contains 19 aircraft, including name, category, weight, wing span, and approach speed. Small aircraft are not included on this listing because spacing behind them is not dictated by their wake.

The default spacing matrix file provides the FAA's current criteria as default spacing parameters. Table 2 describes the FAA criteria at the runway threshold window. This file also gives the minimum aircraft spacing at the threshold for ROT considerations.

AVOSS Outputs

The AVOSS code produces several output file types. The output used in this analysis contains aircraft separation matrices for each defined window in the corridor and the "approach spacing" required at the start of the approach path. The separations are defined for each pair of aircraft weight classes, i.e., large aircraft following heavy aircraft. The analysis in this report only makes use of the approach spacing values.

Post-processing

Post-processing was performed on the AVOSS-provided approach spacing values to estimate the resulting runway throughput, or potential arrival rate. When estimating throughput an attempt was made to also estimate the effect of practical ATC use of the

AVOSS data. For example the AVOSS provides spacing outputs to the nearest 0.01 NM (i.e., 3.67 NM) while controllers may require presentation of 1/2 or 1 nautical mile increments.

The first phase of post-processing involved a rounding scheme used to analyze the effect of the ATC interface on AVOSS performance. In this study the rounding interval was either 0.5 NM or 1.0 NM. A conservative rounding rule was employed to minimize rounding down to lower spacing than required. For this study, 10% of the rounding interval is needed to "round up" the approach spacing. For example, if the rounding interval is 1.0 NM, any number greater than 3 and less than 3.1 would round down to 3 and any number between 3.1 and 4 would round up to 4. This method of rounding minimizes the truncation error by limiting the possibility of "rounding down."

The post-processing, or data reduction, performed for this study are estimated throughput values, which are based on the rounded AVOSS separation values, ATC time variance, aircraft speeds, and the probability of encountering each aircraft class in the traffic mix[3]. The time variance is a quantification of the spacing buffer that controllers use to insure spacing regulations are not violated. For this study, the throughput estimates are based on the Dallas/Fort Worth traffic mix, which consists of 25% small aircraft, 60% large aircraft, 10% Boeing 757, and 5% heavy aircraft[1]. To calculate throughput, a probability matrix p is defined:

$$_i = follower\_aircraft$$

$$_j = generator\_aircraft$$

$$p_{ij} = probability_i \times probability_j$$

where p_{ij} is the probability of aircraft i following aircraft j.

A product matrix is then defined:

$$prod_{ij} = p_{ij}\left(\frac{separation_{ij}}{velocity_i} + buffer\right)$$

where (from reference 3):

$$buffer = 1.65(ATC\ var)$$

and

$$\left(\frac{separation_{ij}}{velocity_i} + buffer\right) = \text{expected time spacing}$$

for pair i,j (seconds).

Throughput is calculated using the sum of the product matrix:

$$throughput = \frac{3600}{\sum_{ij} prod_{ij}} \quad \text{(aircraft/hr)}$$

EXPERIMENT DESIGN

This experiment uses the batch mode of the AVOSS code. In other words, the code reads weather and configuration data from archived files instead of reading from instrument output files as it would in the field. The weather inputs used in this study are not observed weather conditions. Instead, synthesized weather conditions are created so that each experimental variable can be systematically manipulated one at a time.

Weather, Configuration, and Post-Processing Experiments

This study contains three sensitivity experiments dealing with weather, system configuration, and post-processing options. The weather experiment evaluates the sensitivity of AVOSS performance to atmospheric conditions. This section of the study shows when AVOSS is most beneficial based on the condition of the atmosphere around the airport. The four weather factors studied are mean crosswind, crosswind variance, turbulent kinetic energy (TKE), and thermal stratification.

The second part of this study explores the effects of the system configuration. This information will help illustrate the tradeoffs between safety factors and system performance. This study investigates the two corridor options and various demise definitions. Additional cases were run with a standard approach window width at the glide slope intercept, rather than a 20-km wide window. The wide window at that point creates a bottleneck in certain weather conditions, because it disables the benefit of high crosswinds. In the absence of the logic to increase the window width at this location, the standard width would be 352 meters. A set of runs was made with a 352 meter wide glide slope intercept window in order to study the severity of this bottleneck.

The post-processing experiment examines the performance loss AVOSS might experience when interfaced with an ATC system. AVOSS outputs spacing matrices to the nearest hundredth of a nautical mile, but information provided to ATC controllers would likely be given at the nearest half or full nautical mile. Also, ATC controllers give each separation a buffer to make sure the spacing minimums are not violated. Therefore, rounding effects and ATC time variances are examined.

Weather and Configuration Sensitivity Baseline

For this study, unless otherwise specified, crosswind variance is set to zero and a neutral thermal stratification is implemented. Corridor option 2 is used and the demise definition is set to a circulation value of 70 m^2/s. The ATC controller variance is ten seconds and there is no rounding of the spacing matrix. Maximum gross landing weight for all 19 aircraft were used for weather and configuration sensitivity testing. The airspeed of the approaching aircraft is assumed to be the reference speed for the heavier aircraft at its maximum landing weight, and slightly higher than reference for the slower aircraft. The higher-than-reference speed for slower aircraft assumes an effort by those crews to accommodate ATC and maximize traffic flow rates. Table 4 lists the baseline run conditions and table 5 describes the aircraft database, weight variations, and baseline approach speed at each weight.

Crosswind Variance	0
Thermal Stratification	Neutral
Corridor Option	2
Demise Definition	70 m^2/s
ATC Controller Variance	10 sec.
Rounding	None
Aircraft Weight	MGLW
Traffic Mix	All 19 aircraft

Table 4 – Weather and Configuration Sensitivity Baseline parameters

Aircraft			Weight (kg) / Base Approach Speed (m/s)				
#	Type	Cat.	Minimum Weight	25%	Mid-Weight	75%	MGLW
			Option 1***	Option 2***	Option 3***	Option 4***	Option 5***
1 **	ATR-72	L	12202 / 49.8	14130 / 52.8	16057 / 55.8	17985 / 58.8	19913 / 61.8
2	Fokker F100	L	23587 / 55.9	27386 / 59.3	31185 / 62.7	34984 / 66.1	38783 / 69.5
3	DC-9	L	33204 / 57.9	37377 / 60.8	41550 / 63.7	45723 / 66.6	49896 / 69.5
4	B-737	L	27443 / 56.4	32716 / 60.4	37989 / 64.3	43262 / 68.2	48535 / 72.1
5	MD80	L	36107 / 56.4	41595 / 59.6	47084 / 62.9	52572 / 66.2	58061 / 69.5
6	A320	L	41278 / 61.2	47084 / 64.5	52890 / 67.9	58696 / 71.2	64502 / 74.6
7	B-727	L	44906 / 58.4	51824 / 61.8	58741 / 65.2	65659 / 68.7	72576 / 72.1
8	B-757	Note 1	58288 / 57.3	66169 / 60.4	74050 / 63.4	81932 / 66.5	89813 / 69.5
9	DC-8	H	68849 / 55.9	82822 / 60.0	96794 / 64.0	110767 / 68.1	124740 / 72.1
10	A310	H	80015 / 59.5	90765 / 62.6	101516 / 65.8	112266 / 68.9	123016 / 72.1
11	B-767	H	83553 / 62.0	94190 / 65.2	104827 / 68.3	115464 / 71.5	126101 / 74.6
12	A300	H	90130 / 61.7	102094 / 64.9	114058 / 68.1	126021 / 71.4	137985 / 74.6
13	L-1011	H	109318 / 63.9	123719 / 67.2	138121 / 70.5	152523 / 73.9	166925 / 77.2
14	A340-200	H	125103 / 58.5	139573 / 61.3	154043 / 64.0	168512 / 66.8	182982 / 69.5
15	DC-10	H	121202 / 60.0	136602 / 63.0	152001 / 66.0	167401 / 69.1	182801 / 72.1
16 *	MD-11	H	126101 / 63.6	143338 / 67.0	160574 / 70.4	177811 / 73.8	195048 / 77.2
17 *	B-777-200	H	138121 / 60.2	155188 / 63.2	172255 / 66.1	189321 / 69.1	206388 / 72.1
18 *	B-747-200	H	170554 / 63.4	194254 / 66.9	217955 / 70.3	241655 / 73.8	265356 / 77.2
19 *	B-747-400	H	177222 / 66.8	204358 / 70.7	231495 / 74.6	258631 / 78.5	285768 / 82.4

Table 5 – Aircraft weights and corresponding approach velocities for aircraft database sensitivity study. MGLW was used in weather and configuration sensitivity testing. (L=Large, H=Heavy)

Notes:
1. The B-757 is treated as a special weight category when it is the wake generator and it is treated as a large aircraft when it is the follower.
2. * indicates this aircraft is not present in the data set in traffic mix option 2 and 3
3. ** indicates this aircraft is not present in the data set in traffic mix option 3
4. *** Weight Options. Weight option 0 (not shown in table, but discussed in text) refers to the case where large aircraft are at maximum gross landing weight and heavy aircraft are at mid-weight

Aircraft Database Sensitivity Experiment

An additional set of runs was conducted to evaluate the effect on AVOSS performance due to changes or uncertainties in the aircraft specifications used to derive wake initial conditions. Three primary and one secondary independent variables were varied. The primary variables were weight, speed, and traffic (aircraft type) selection and the secondary was the weather environment. Table 6 shows the weather conditions used.

In general, aircraft weight and planned speed on final are not known by ground systems in advance of the approach. It is highly desirable, from the standpoint of practical implementation, to avoid the need for actual weight or speed data in an operational AVOSS system. This is the first in a series of studies to determine the potential performance impact of unknown weight and airspeed.

Although AVOSS has the potential to interface to ATC and provide aircraft-type specific separation requirements, the current AVOSS project and

Weather Option	Crosswind	TKE	Stratification
1	1 m/s (calm)	0.02	Neutral
2	1	1.00	Neutral
3	1	0.02	Stable
4	4 m/s (windy)	0.02	Neutral
5	4	1.00	Unstable

Table 6 – Weather Options For Aircraft Database Sensitivity Study

Notes:
1. Head wind is set to zero in all cases.
2. Crosswind variance is set to 1 m/s in all cases.

demonstration are performed off-line from ATC and AVOSS is designed to produce weight-category-based separation values that accommodate the worst-case aircraft-type pair within the category. The full aircraft database was designed to approximate a worst-case traffic mix for the runs conducted in this report. Two factors affect the selection of aircraft for worst-case. The heaviest aircraft within each weight category, particularly with short wing span, will produce the strongest wakes with potentially the longest times to demise. This aircraft may produce the worst-case separation interval when wake decay dominates the separation. Aircraft with light weights and large wing spans will tend to have the slowest wake sink rates. These aircraft may become worst-case when wake drift and sink are dominating the separation criteria. The evaluation being conducted here is a first step to determine the improvements in separation that might be realized by tailoring the wake predictions to the actual traffic mix.

The baseline weight chosen for each aircraft type was mid-way between the empty landing weight and the maximum landing weight. The weight was varied in 25 percent increments of the interval between empty weight and maximum gross landing weight. In these five conditions the weights of all aircraft were varied at the same time. An additional condition, labeled Option 0, was run where the heavy category aircraft were assumed to be at their mid-weight, and the large aircraft were assumed to be at their maximum weight. This weight condition simulates a scenario where most heavy aircraft are landing after long flights and the large aircraft are landing after short flights. In all cases the aircraft final approach speed was also varied as would be expected with the weight change. The speed change provided was one-half the percent of weight change, to preserve a constant lift coefficient at each weight. The physical effect of weight changes within AVOSS is two-fold. Increasing weight tends to produce stronger wakes, that will take longer to decay, but will take less time to descend below the corridor floor. The effect could be to increase or decrease the separation time interval, depending on the factor dominating separation. Second, the speed change that accompanies the weight change can cause the distance-based spacing to change even when the time-based spacing remains the same.

Five speed conditions are simulated. The baseline speed is the reference speed for the mid-weight of the aircraft. From this base the speed is varied -10%, -5%, +5%, and +10%. The speed of all aircraft types and the follower and generator are varied at the same time, so this study does not reflect the effect on spacing due to increased variation in speed between aircraft, that is,

all B-727 aircraft are assumed to have the same speed while in actuality some B-727 aircraft in a queue may fly faster than others.

Three aircraft mixes are simulated. The baseline is the 19-aircraft set normally run by AVOSS. The second option removes the four heaviest aircraft from this set. This option eliminates the MD-11, B-777, and two variants of the B-747 from the mix. This selection leaves the DC-10 as the heaviest aircraft in the mix. The third option is the same as option 2, with the ATR-72 removed from the large category. The ATR-72 is a special case, since it is one of the smallest aircraft in the large category, has a large wing span for its weight, and has a minimal initial wake strength. While its wake would generally not be a hazard to most following aircraft, the combination of a large wing span and a weak wake produces a slow-sinking wake that will remain for longer than normal periods in the approach corridor.

Changing the aircraft mix also affects the calculation of approach spacing required to meet all window spacing requirements. These equations use the maximum speed of the aircraft in the follower category, and the speed of each generator type, to calculate the change in spacing expected during the final descent. When aircraft are eliminated from the mix then the speeds used in these calculations also change. For example the fastest aircraft in the heavy category is the B-747-400 at 82.4 m/s (160 knots). Removing the B-747-400 not only removes the strongest wake from the heavy generator category, but also reduces the maximum speed of the heavy category from 82.4 m/s (160 knots) to 77.2 m/s (150 knots) when calculating the distance that heavy followers must have at the spacing point to meet spacing constraints at the threshold.

Five variations of the secondary variable, weather, were used. Weather was varied to ensure that aircraft data base sensitivity results were not biased by the weather condition chosen. For example a high-wind weather condition could have quickly moved wakes out of the corridor, masking sensitivity to initial wake strengths. Table 6 shows the weather conditions. Calm winds with low and high turbulence values were used to prevent masking different wake sink rate and decay trends due to the different initial wake strengths. Calm winds with low turbulence and stable stratification was used to allow wake buoyancy terms to affect the sink rate of different initial wakes. Two "windy" cases with significant crosswind were used, one with low turbulence and neutral stratification and one with higher turbulence and unstable stratification. In all cases the head wind component was zero at all altitudes. Head wind has no effect on predicted wake behavior in the

current AVOSS implementation and is only used to estimate aircraft ground speed for approach spacing calculations.

Aircraft Database Sensitivity Baseline

For this study, unless otherwise specified, crosswind variance is set to zero. Corridor option 2 is used and the demise definition is set to 70 m^2/s. For aircraft database sensitivity testing, aircraft mid-weight, zero speed change, and all 19 aircraft are the baseline values. Table 7 lists the baseline values. Table 5 lists the aircraft weights and corresponding speeds used in the aircraft database sensitivity study.

Study Limitations

This study represents the first sensitivity study of AVOSS separation matrices to ambient weather and system configuration options. Several aspects of the current AVOSS implementation limit the applicability of the results. These factors include:

1. The wake vortex predictor algorithm[4,5] in use does not model vertical wind shear effects on wake trajectory. The vertical shear data provided in the wind profiles is not used.
2. The wake vortex algorithm does not model accelerated wake decay rates in ground effect. During the first time step in ground effect the model computes the decay rate due solely to ambient turbulence and thermal conditions. That decay rate is fixed for all subsequent time steps. For wakes initially generated in ground effect, an empirical reduction in the initial wake strength is used to better match observed data.
3. The present implementation uses a single wake demise definition for both large and heavy follower aircraft, and does not use wake demise to reduce spacing for small follower aircraft. Analysis suggests that heavy aircraft are immune to adverse wake effects at a wake strength above ambient background turbulence[1,6]. Use of a category-dependent demise definition would improve performance.
4. The post-processing provided is a first approximation to the effects of an actual ATC interface and may under-estimate or over-estimate losses in efficiency. Use of advanced ATC aids such as the Center-TRACON Automation System (CTAS) may recover much of the losses that would occur in an interface to a present-day ATC environment.
5. The results are applicable to the particular implementation of AVOSS studied. This implementation uses a safety corridor concept for

Crosswind Variance	0
Corridor Option	2
Demise Definition	70 m^2/s
Approach Speed Change	0 percent
Aircraft Weight	Mid-weight
Traffic Mix	All 19 aircraft

Table 7 – Aircraft Database Sensitivity Baseline parameters

reduction of approach spacing for aircraft in-trail to a single runway. Systems tailored for departure or for parallel runway applications will have different performance characteristics. Likewise many design decisions of the current system affect spacing. Examples include category-based spacing rather than aircraft-type-based spacing, disabling of wake lateral drift as a spacing reduction factor at the glide slope intercept, disabling of wake demise as a spacing reduction factor for small followers, and the statistical uncertainty techniques used. The current system assumes that the probability of a wake encounter is unity if the wake is not predicted to be out of the corridor while the probability of a wake encounter may be lower in many of these situations than is the case today during visual approaches.

Advancements in wake vortex behavior prediction are resulting from ongoing AVOSS efforts[7,8,9,10] and will be incorporated into the next generation AVOSS system planned for demonstration in the year 2000.

RESULTS AND DISCUSSION

Runway throughput increase is the primary measure of AVOSS benefit used in this study. Most of the AVOSS performance figures are presented in terms of the runway throughput increase. The increase is expressed in terms of the percent increase in the maximum possible runway arrival rate resulting from use of AVOSS spacing, relative to the FAA-defined spacing values. If runway throughput is estimated to be 35 aircraft per hour with the FAA spacing criteria and 38.5 with AVOSS reduced spacing, the result is a 10% throughput increase. When rounding is studied in this experiment, only the reduced approach spacing matrix is rounded. The default approach spacing matrix, calculated from FAA threshold spacing criteria, is assumed to be the spacing in the absence of AVOSS and is always used as-is without rounding for throughput computation.

Statistical weather data[11] collected at Dallas/Fort Worth International Airport was used to relate the results of this study with typical weather conditions observed at DFW. Weather data collected for a 30-year period indicate surface crosswind exceeds 3 m/s in less than 20% of the observations. Based on statistics compiled by Lincoln Laboratory at DFW, eddy dissipation rate (EDR) exceeds 0.001 in about 50% of observations and exceeds 0.01 in less than 10% of the observations at 40 meters above the surface. Analysis of AVOSS field data by NorthWest Research Associates indicates that these EDR values are roughly equivalent to TKE values of 0.5 m^2/s^2 and 2 m^2/s^2, respectively, when TKE is computed at a 5-minute period. While these data were collected near the surface for the purpose of the discussion below the statistics will be assumed constant with altitude. Generally, however, wind speeds would be expected to be somewhat higher on average at higher approach altitude than indicated here.

Weather and Configuration Sensitivity

The effect of crosswind and TKE on throughput is illustrated by the crosswind-TKE surface plots of figures 1 and 2, for corridor options 1 and 2, respectively. Figures 3 and 4 provide cross-section slices through the data in figure 2, for specific TKE or crosswind conditions, respectively.

Crosswind

Spacing variations and throughput are extremely sensitive to crosswind, but only for a narrow crosswind interval which depends on TKE. The most sensitive interval increased throughput by 12.7% per one m/s of crosswind. The crosswind value where the rapid throughput change occurs varies with the ambient turbulence. For every one m^2/s^2 increase in TKE, the required crosswind increases by roughly 0.5 m/s, as shown by figure 3. Higher turbulence values require a higher crosswind to achieve the same spacing due to the increased decay rate, and associated decreased sink and drift rates, of the wakes in the higher turbulence.

Both sides of the region of rapid throughput change show a positive throughput increase relative to the default separation matrix, but each side can differ in throughput increase by 4 to 15 percentage points. Outside this region, AVOSS is insensitive to crosswind with respect to throughput. Therefore wind instruments need to be accurate enough to tell if weather conditions point to the "high" or "low" side of this crosswind interval.

AVOSS performs better during steady wind conditions. Variance in crosswind counteracts the benefit gained

from the crosswind itself. Crosswind variance delays the effect of crosswind, but does not reduce the maximum throughput increase. Every unit of crosswind variance delays the effect of crosswind by one unit. In other words, crosswind would have to increase one m/s for every m/s of crosswind variance to get the same spacing matrix. More crosswind is needed in variable wind conditions to achieve the same throughput values as is required in steady wind conditions. If the variance, or uncertainty, is too high, then statistically, the benefit of AVOSS will be significantly reduced. The wind variance can be high for at least two reasons, the actual wind may be highly variable, for example in certain convective weather situations, or the method of estimating variance may produce high values due to instrument discrepancies. Since the crosswind is statistically low much of the time, this results suggests that effective means of estimating wind variance must be implemented for optimal performance.

It is important to note that, in this study, wind mean and variance were varied uniformly at all altitudes. The wake transport out of the safety corridor is completely dependant on lateral drift close to the ground, and is aided by wake sinking motion above about 60 meters altitude. At the glide slope intercept the wake transport is completely dependent on wake sinking motion. For these reasons the study may have shown less sensitivity to variance increases only at higher altitudes. Future studies should determine if the criticality of variance estimation is reduced at higher altitudes, hence potentially reducing the demands on an operational weather system.

Turbulence

The system shows no consistent trend of throughput with respect to turbulence. At very low crosswind values the throughput increase is very low at low turbulence values and increases with turbulence. At high crosswind values the throughput increase is substantial with low turbulence and decreases with increasing turbulence. Once the throughput increase reaches a minima, further turbulence increases improve throughput slightly. The sensitivity to TKE is strongest in low TKE and crosswind conditions. Unlike crosswind, TKE affects throughput outside the region of high sensitivity. These effects can be observed in figure 4 as well as in the surface plots of figures 1 and 2.

The relationship between wake decay and wake motion influence the throughput sensitivity of AVOSS to turbulence. At low crosswind values the wakes do not reliably drift away form the approach path when in

ground effect, and turbulence must operate to cause wake demise if spacing is to be reduced. Much of the benefit of turbulence is realized at a moderate value of 1 m^2/s^2. In high crosswind conditions, where high is defined as about 1.5 m/s (3 knots) with zero variance, wake drift becomes highly effective in reducing spacing. Turbulence becomes counter-productive in this wind condition by accelerating decay and reducing the wake sink rate and lateral drift rate in ground effect.

The sensitivity to turbulence in high crosswind is dependent on the corridor option chosen. Because the approach corridor window at the glide slope intercept altitude is extremely wide, crosswind has no effect on residence time in this area. Any spacing reduction due to wake motion will rely only on the wake sinking behavior at this location. Turbulence acts to decrease the sink rate. Comparison of figures 1 and 2 shows the effect of the corridor depth on this sensitivity. Corridor option 1 (figure 1) shows throughput sensitivity to turbulence at very low TKE values. A TKE value of only 0.125 m^2/s^2 is required to prevent the wake from sinking below the corridor floor before demise occurs. Above this TKE level the spacing is dependent on wake decay. Corridor option 2 (figure 2) does not show this transition from sink rate to demise as the controlling factor until the TKE reaches 2 m^2/s^2. This result suggests that common TKE levels may prevent wake sinking below the corridor floor, in time for spacing reduction, for option 1 while high turbulence levels are required to produce this effect for option 2. The dependence on wake sink and demise at high altitude is an artifact of disallowing the use of lateral wake motion at the glide slope intercept for spacing reduction. A different technique for accommodating the aircraft merge onto the localizer may potentially remove this effect and lead to improved performance in high crosswind and turbulence conditions.

Thermal Stratification

AVOSS shows little sensitivity to thermal stratification in most cases. Unstable, neutral and inversion stratifications varied in spacing only by a few hundredths of a mile from each other in all cases studied. The exception is for stable stratification where the effect of TKE is exaggerated. The stable gradient reduced the spacing behind heavy generators by about 25% for large followers and 12.5% for heavy followers. Figure 5 demonstrates the effect of stratification for large and heavy aircraft following heavy generators at different TKE values. In these cases, the stable stratification increases the wake decay rate and reduces the worst-case residence time in the outer window by 30 seconds. Spacing was not governed by sink rate in these cases so the reduced sink rate did not increase

spacing. Since strongly stable stratification is generally not consistent with high turbulence values, this sensitivity increase is taking place in an improbable weather domain. Spacing behind large generators was not significantly affected.

Thermal gradient measurements are important only when dealing with heavy generators. In these cases, spacing differences of up to one nautical mile were noticed in this study. Overall, however, thermal gradient differences proved insignificant for two reasons. First of all, the spacing differences for heavy generators occurred in regions outside the region of most probable weather defined earlier in this section. Secondly, overall throughput increase was only marginally affected by the heavy generator results due to the low ratio (5%) of heavy aircraft. Therefore, the thermal gradient effect would have been more pronounced using a traffic mix with a higher probability of heavy aircraft.

Configuration, Corridor Option

Corridor floor option 1 creates lower throughput increases than option 2 in common values of TKE. The difference can be as much as 7-8% during low TKE (0.125 m^2/s^2) and high crosswind. Corridor option 1 is very similar to option 2 in the rare conditions when TKE is above 4 m^2/s^2. TKE-crosswind surface plots for corridor options 1 and 2 are shown in figures 1 and 2.

Corridor option 2 achieves a better throughput, but assumes better navigational accuracy. Because option 2 has a smaller vertical dimension than option 1, vortices can sink below the corridor floor more quickly, allowing approach spacing to be reduced. The decision on which option to use for actual AVOSS operation should be based on what industry and the FAA consider a reasonable glide slope tolerance based on pilot and instrument precision.

When the step increase of the approach corridor width at the glide slope intercept altitude was eliminated, horizontal transport time became the governing factor for residence time during high crosswind. This change eliminated the AVOSS sensitivity to TKE in high crosswind conditions and produced an additional throughput increase of as much as 6.5% for corridor option 1 and 5% for option 2. The maximum benefit occurred when TKE was between 1 and 3 and crosswind was greater than 3 m/s. The maximum benefit occurs outside the most probable weather conditions, but gains in throughput can be as high as 2% relative to the baseline AVOSS when using the reduced approach window width in the probable weather defined above. Figure 6 and a comparison

between figures 2 and 7 demonstrate the effect of the 20 km step increase of the approach window.

Configuration, Wake Demise Definition

Increasing the demise threshold increased throughput gain only slightly. The differences are most noticeable in areas of moderate TKE. Demise is the controlling factor for residence time in these cases, and a higher demise value produces a shorter decay time. The maximum observed increase in throughput was only one percent when using a demise definition of 110 m^2/s instead of 70 m^2/s. Therefore, little is gained by increasing the demise definition. Thus, demise can be set low without any significant loss in AVOSS performance. Figure 8 shows this minor increase in throughput.

Configuration, ATC Interface Post-processing

The variance of actual aircraft spacing about the desired spacing, or the ATC controller variance, reduces the overall performance of AVOSS. The percent throughput increase is reduced by roughly 1.5% of the zero variance value for each second of controller variance. For example, if throughput increase is 15% for zero ATC variance, then a throughput increase of roughly 12.75% would be observed for an ATC variance of 10 seconds. The effect of spacing variance is shown in figure 9.

Better ATC system spacing precision leads to a better realization of AVOSS capabilities. If the equipment used by controllers improves such that they can improve spacing precision, AVOSS performance will be maximized. Spacing precision is a characteristic of the ATC system and not controllable by AVOSS.

Rounding by 0.5 NM intervals decrements the throughput increase by 4 to 6 percent, but rounding by 1 NM intervals degrades performance by only one percent more. If a throughput increase of 12% is observed with no rounding, throughput increases of 6 to 8% and 5 to 7% would be observed for rounding of 0.5 NM and 1 NM intervals respectively. An example of rounding effects is shown in figure 10.

Aircraft Database Sensitivity

Aircraft Speed

The spacing between most aircraft pairs was insensitive to speed changes. The exception was for small followers, where spacing increased 1.2 to 1.5 NM for a 10% speed increase in some weather conditions. Increasing speeds by 10% produced approach spacing

increases of 0.25 to 1.2 NM behind heavy generators only during conditions of high crosswind and high turbulence. Therefore, higher speeds in the aircraft database gave worst-case spacing. The increased spacing in this case does not imply a throughput penalty. In the spacing plots shown in figure 11, the throughput was 32.5 aircraft per hour for the -10% speed option, then 32.3, 32.0, 31.8, and 31.4 aircraft per hour for the -5% through +10% speed options, respectively. The throughput itself only varied 3% from each extreme. The increased spacing was therefore largely due to the kinematics of converting a relatively constant time spacing into a distance based spacing at various speeds. Higher speeds require more distance for the same wake residence time values. Also, when computing the distance required at the top of the approach to meet wake constraints at all approach locations, a greater speed difference between aircraft will create higher "approach" spacing values. Figure 11 is an example of how aircraft speed affects the spacing matrix.

Aircraft Weight

No consistent trend was noted when altering the aircraft weights in the database. Weight changes could produce a spacing increase or decrease depending on the aircraft pair and whether wake decay or wake sink rate was dominating the spacing values. When increasing weight from empty weight to maximum weight, spacing decreased by up to 2.4 NM for small followers in some weather conditions. Higher weights can lead to reduced following distance when wake transport time is the controlling spacing factor. Wake transport times for heavier aircraft tend to be shorter because stronger wakes descend faster. For large and heavy aircraft following heavy aircraft, spacing varied only 0.4 NM between weight options. Heavy aircraft following B-757 or large aircraft were generally insensitive to weight changes. Figure 12 shows the effect of aircraft weight on spacing. The throughput values for weight options 0 through 5 were 32.4, 30.4, 31.3, 32.0, 32.7, and 33.1 aircraft per hour, respectively. Hence, use of maximum landing weights in the aircraft data base is not the most conservative choice.

Aircraft Traffic Mix

Changing the aircraft inventory in the aircraft database affected spacing in these cases: (1) removing the four heaviest aircraft from the database (options 2 and 3) reduced spacing for heavy followers by roughly 0.4 NM and (2) removing the ATR-72 (options 3) reduced spacing for all follower categories behind large generators by 0.3 to 0.8 NM. Figure 13 illustrates how traffic mix inputs into AVOSS can affect the spacing

matrix. The throughput values for options 1, 2 and 3 are 30.3, 30.4, and 33.4 aircraft per hour, respectively. This result suggests that tailoring the aircraft data base to the aircraft types using the airport, or expected to use the airport in the next period, may significantly effect throughput if a large number of heavy aircraft use the airport, or if an aircraft such as the ATR-72 is mixed with a large number of large aircraft.

Using the original 19 aircraft in the database gave worst-case spacing. The ATR-72 and the four heaviest aircraft were required in the aircraft database to provide worst-case wake sink rate and demise values. Tailoring the aircraft database to the actual arrival traffic mix has the potential to improve system performance.

SUMMARY

A study was conducted to determine the sensitivity of the Aircraft VOrtex Spacing System (AVOSS) aircraft separation value and runway throughput calculations to various system input and configuration changes. Weather inputs, aircraft data parameters, and AVOSS parameters were systematically varied to determine their impact on system performance. The purpose of this study is to determine which parameters must be accurately characterized by the system and which may have secondary effects.

The results suggest that runway throughput is highly dependent on ambient wind and turbulence, but much less so for thermal stratification in most conditions. The throughput is generally not linearly influenced by wind or turbulence, but shows relatively little sensitivity outside a narrow range of high sensitivity. The range of wind and turbulence values that produce high system sensitivity are within the range of frequently observed conditions, suggesting that accurate estimates of wind mean and variance are required for optimal performance. An additional study is required to determine if this requirement applies at all altitudes or only near the surface where wake lateral drift is a critical factor for spacing.

The actual spacing required is governed by a complex relationship between the safety corridor shape and wake factors of sink rate, drift rate, and decay rate at different altitudes. The results show that no single wake factor controls separation at all altitudes for all aircraft, and that a system-level evaluation is required to determine the capacity benefit from any single wake factor or design change. For example, an increase in aircraft weight or in wake decay rates may either increase or decrease spacing depending on whether the spacing is being governed by wake motion or wake decay, which

in turn is a function of the weather conditions and the corridor shape.

The system performance showed moderate sensitivity to the safety corridor shape and low sensitivity to the wake demise definition. The results suggest that a very conservative corridor can be used during initial implementation, permitting meaningful capacity gains. The corridor shape can be refined at a later date to improve performance, as confidence is gained in the wake predictions or as improved aircraft navigational performance is realized. Conservative wake demise definitions can be applied without impacting system performance.

In most cases the spacing was not highly sensitive to changes in the assumed aircraft conditions of weight or speed. Much of the spacing difference observed when changing aircraft speeds is due to the kinematics of computing top-of-approach spacing from time-based separation requirements. At higher speeds a greater distance is required to maintain the same time interval and throughput. Also, as all aircraft increase speed the difference in aircraft speeds increases, requiring larger spacing to accommodate spacing compression on final. The most significant sensitivity was a decrease in spacing for small followers behind other aircraft as weights increased. This reduction was due to a decrease in time required for wakes to leave the corridor as weights increase, and a design feature, in this particular system configuration, that never allows spacing for small followers to be reduced due to wake demise. For the small followers the worst-case scenario is to have all aircraft at minimum weight. For large and heavy followers almost no spacing change was required as weights changed. Some spacing reduction was possible when the traffic mix used for wake prediction was altered to remove the heaviest aircraft and the slow-sinking wake of the ATR-72. Overall, the aircraft sensitivity experiments suggest that advance knowledge of aircraft weight and final approach speed is not required for effective AVOSS operation, but that some additional capacity gain is possible from advance knowledge of the aircraft types arriving.

The results of this study are being used in the development of a second-generation AVOSS system, intended for demonstration at the Dallas-Fort Worth Airport in 2000.

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[1] Hinton, David A; Charnock, James K.; Bagwell, Donald R.; and Grigsby, Donner: *NASA Aircraft Vortex Spacing System Development Status,* AIAA 99-0753, 37th Aerospace Sciences Meeting & Exhibit, January 11-14, 1999, Reno, NV.

[2] Hinton, David A.: *Aircraft Vortex Spacing System (AVOSS) Conceptual Design*, NASA TM-110184, August 1995.

[3] Credeur, Leonard; Capron, William R.; Lohr, Gary W.; Crawford, Daniel J.; Tang, Dershuen A.; and Rodgers, William G., Jr.: *Final-Approach Spacing Aids (FASA) Evaluation for Terminal-Area, Time-Based Air Traffic Control*, NASA TP-3399, December, 1993.

[4] Robins, Robert E.; Delisi, Donald P.; Greene, George C.: *Development and Validation of a Wake Vortex Prediction Algorithm*, AIAA 98-0665, 36th Aerospace Sciences Meeting & Exhibit, January 12-15, 1998, Reno, NV.

[5] Robins, Robert E. and Delisi, Donald P.: *Further Development of a Wake Vortex Predictor Algorithm and Comparisons to Data*, AIAA 99-0757, 37th AIAA Aerospace Sciences Meeting & Exhibit, January 11-14, 1999, Reno, NV.

[6] Stewart, Eric C.: *A Piloted Simulation Study of Wake Turbulence on Final Approach*, AIAA Atmospheric Flight Mechanics Conference and Exhibit, AIAA-98-4339, August 10-12, 1998.

[7] Sarpkaya, T.: *Decay of Wake Vortices of Large Aircraft*, AIAA 98-0592, 36th Aerospace Sciences Meeting & Exhibit, January 12-15, 1998, Reno, NV. Also see AIAA Journal, Vol. 36, Number 9, Pages 1671-1679.

[8] Proctor, Fred H. and Han, Jongil: *Numerical Study of Wake Vortex Interaction with the Ground Using the Terminal Area Simulation System*, AIAA 99-0754, 37th AIAA Aerospace Sciences Meeting & Exhibit, January 11-14, 1999, Reno, NV.

[9] Shen, Shaohua; Ding, Feng; Han, Jongil; Lin, Yuh-Lang; Arya, S. Pal; and Proctor, Fred H.: *Numerical Modeling Studies of Wake Vortices: Real Case Simulations*, AIAA 99-0755, 37th AIAA Aerospace Sciences Meeting & Exhibit, January 11-14, 1999, Reno, NV.

[10] Sarpkaya, T.: *A New Model for Vortex Decay in the Atmosphere*, AIAA 99-0761, 37th AIAA Aerospace Sciences Meeting & Exhibit, January 11-14, 1999, Reno, NV.

[11] Solar and Meteorological Surface Observation Network (SAMSON) CD-ROM data base, years 1961-1990, Version 1.0, U.S. Dept. of Commerce and U.S. Dept. of Energy, September 1993, available from National Climatic Data Center, Asheville, NC.
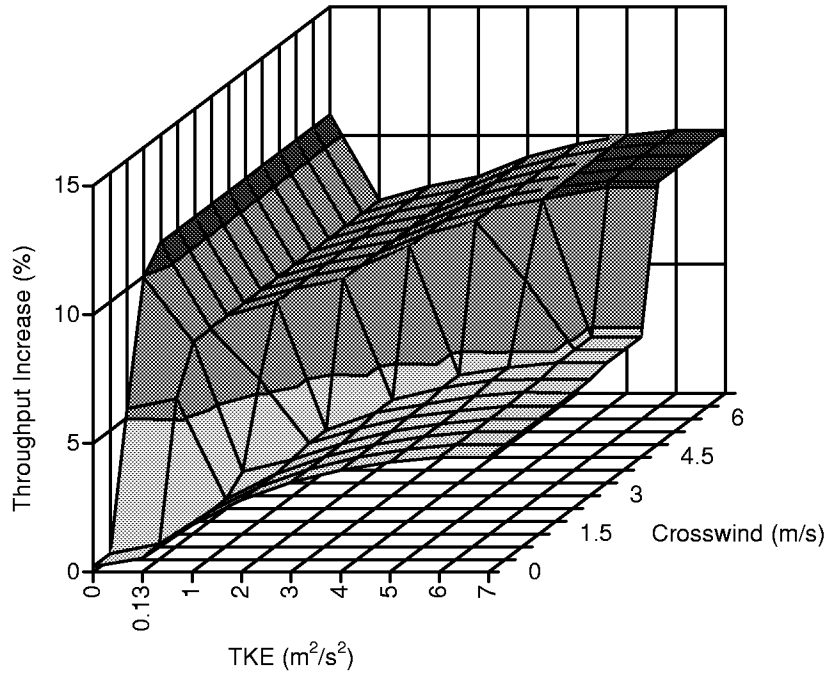
Figure 1 – Runway throughput increase (%) vs. crosswind-TKE. (Corridor option 1)
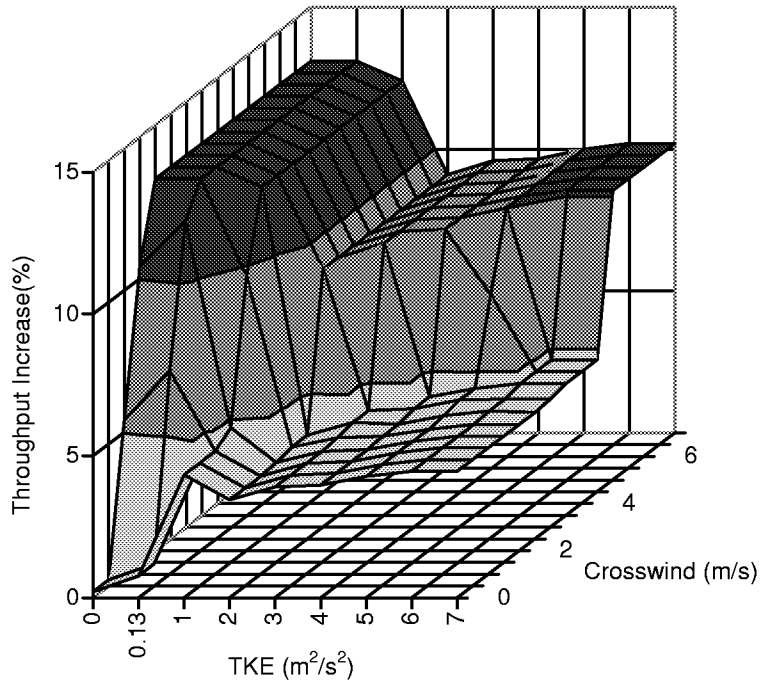
Figure 2 – Runway throughput increase (%) vs. crosswind-TKE. (Corridor option 2)
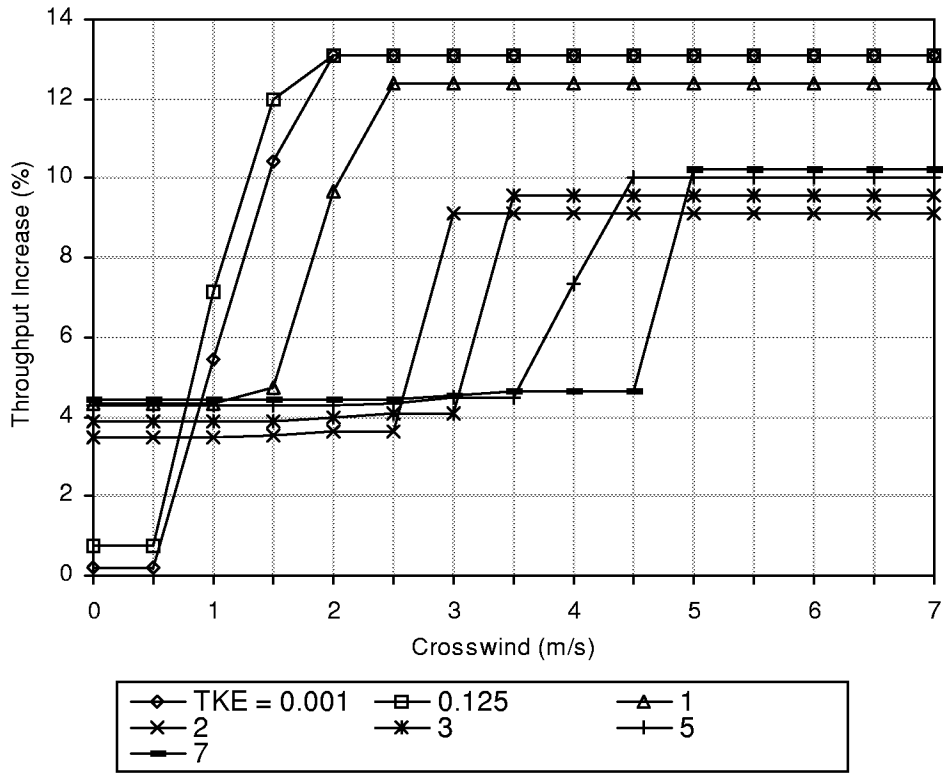
Figure 3 – Runway throughput increase vs. crosswind at various TKE values for corridor option 2.
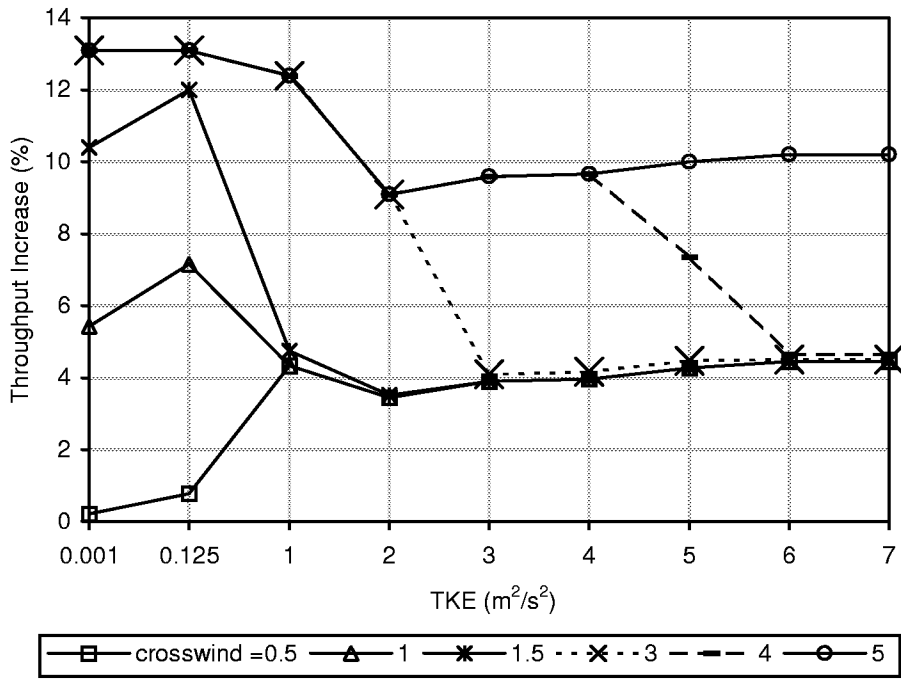

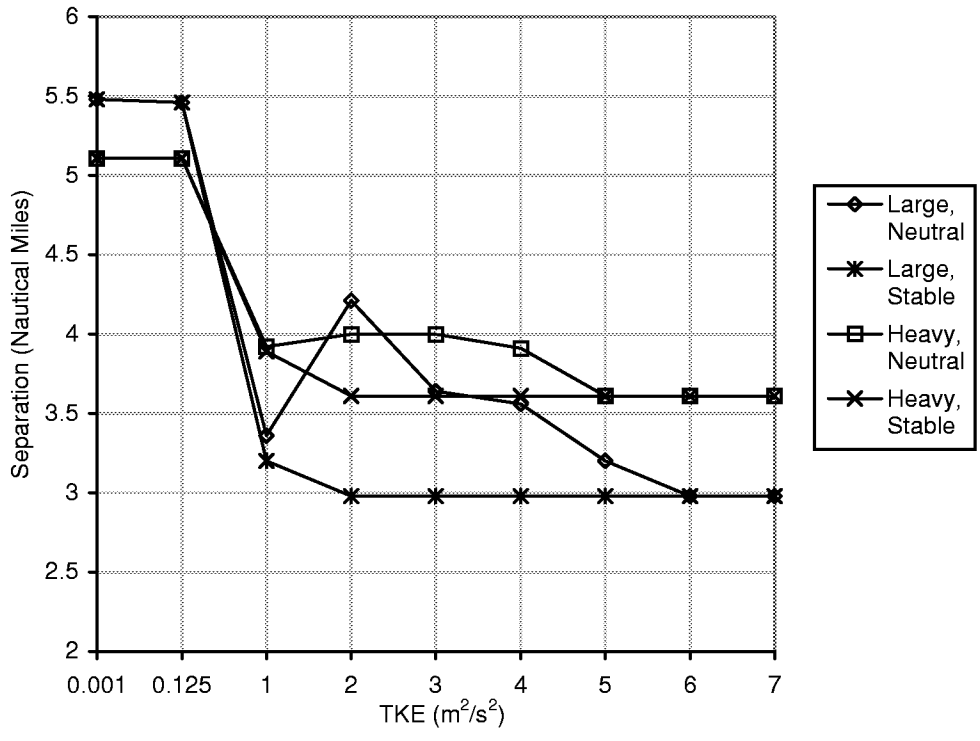*Figure 4 – Runway throughput increase vs. TKE at various crosswind values for corridor option 2.*

Figure 5 – Spacing behind heavy generators for large and heavy followers with neutral and stable thermal stratification. (Crosswind = 0.5 m/s)
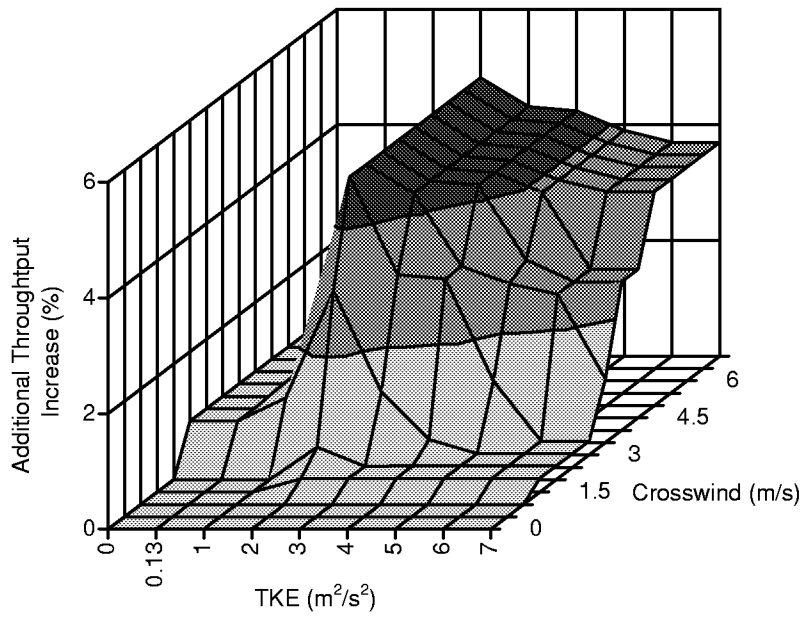
Figure 6 – Additional benefit of enabling use of wake lateral drift at the approach window, relative to default spacing throughput. (Corridor option 2)
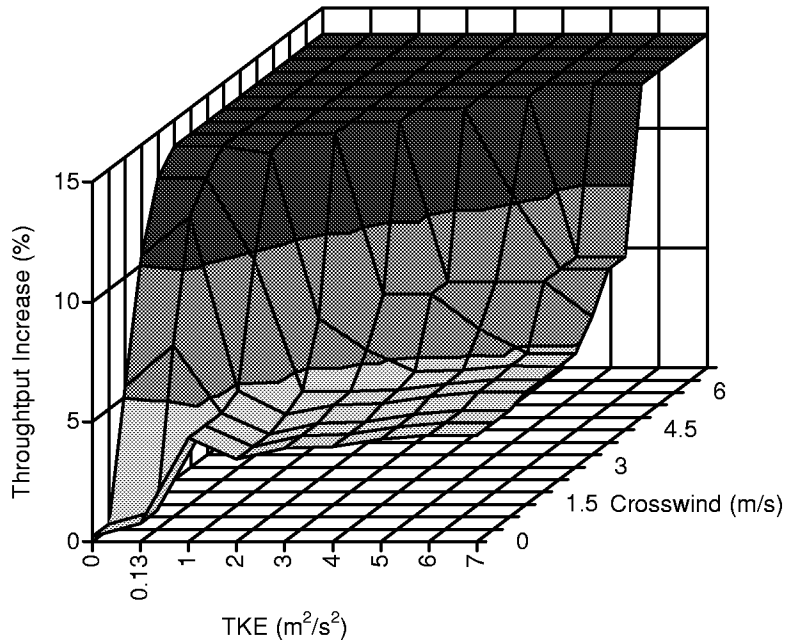
Figure 7 – Runway throughput increase vs. crosswind-TKE, with step window width increase at the approach window eliminated. (Corridor option 2)
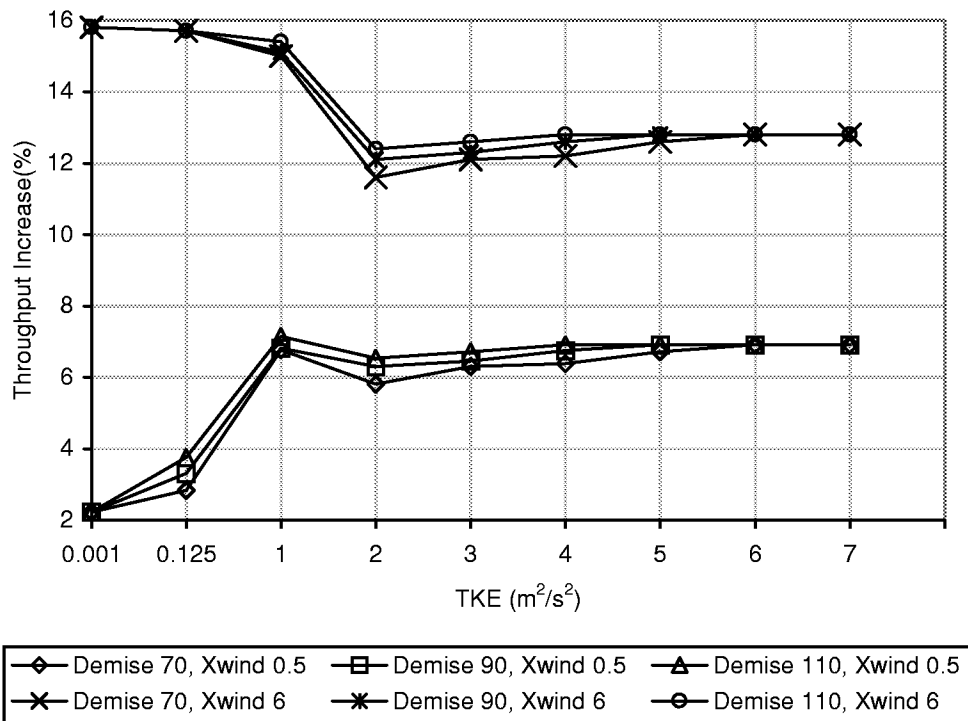
Figure 8 – Runway throughput increase at different wake demise, crosswind, and TKE values.
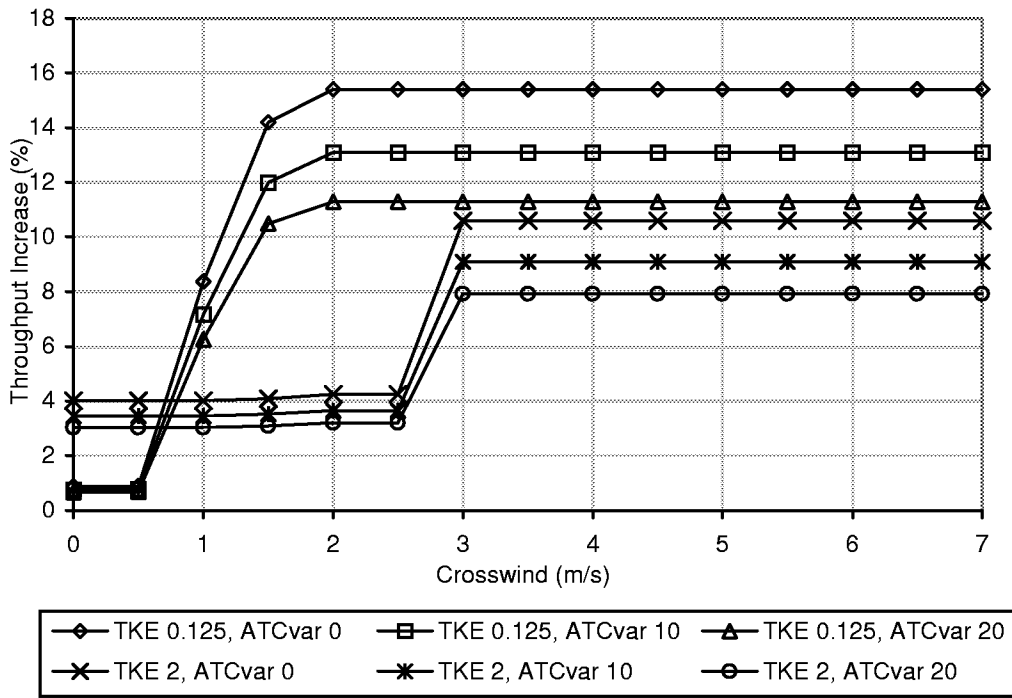
Figure 9 – The effect of ATC time variance on AVOSS performance in various weather conditions.
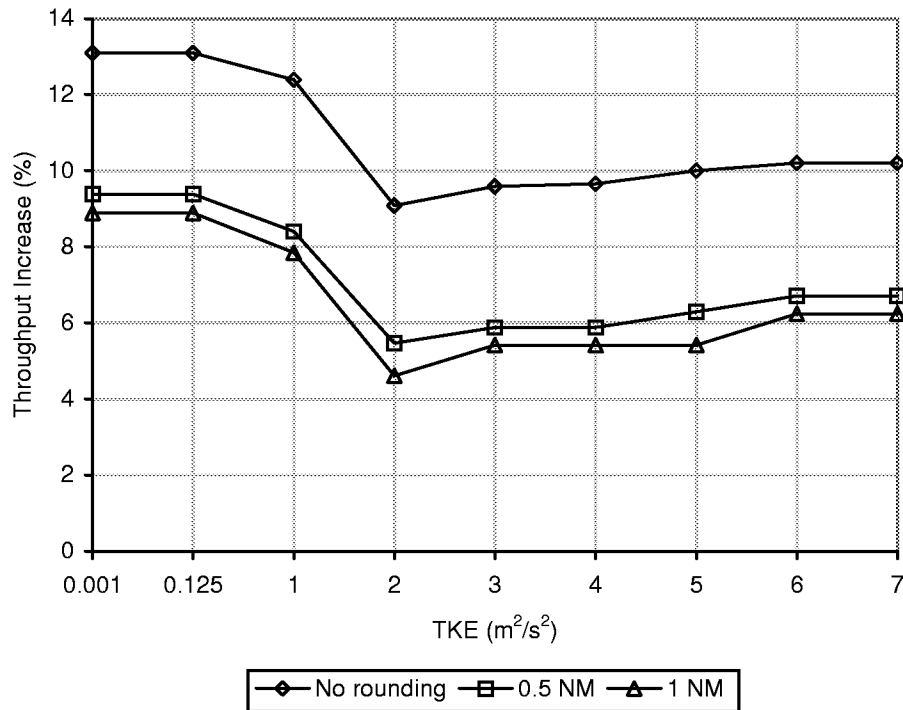
Figure 10 – System performance vs. rounding interval used for spacing outputs.
Crosswind = 5 m/s
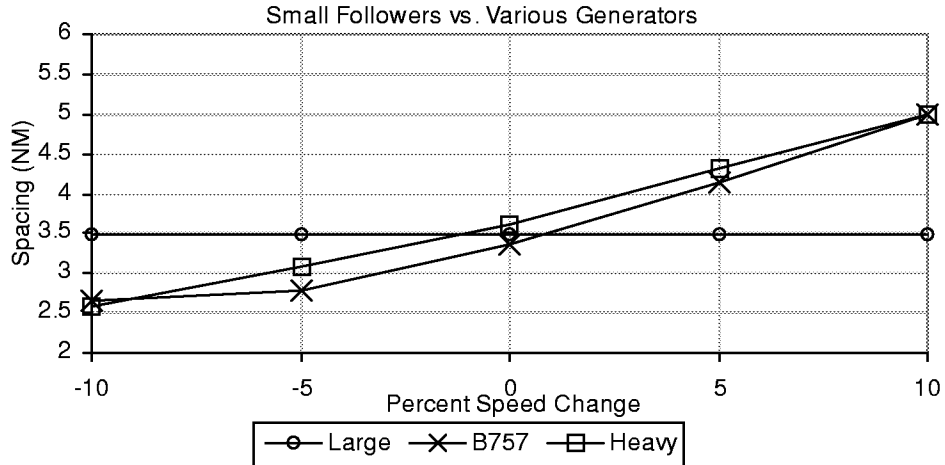
Figure 11a – Spacing changes due to uncertainty in aircraft approach speeds. (Windy, High TKE, Unstable)
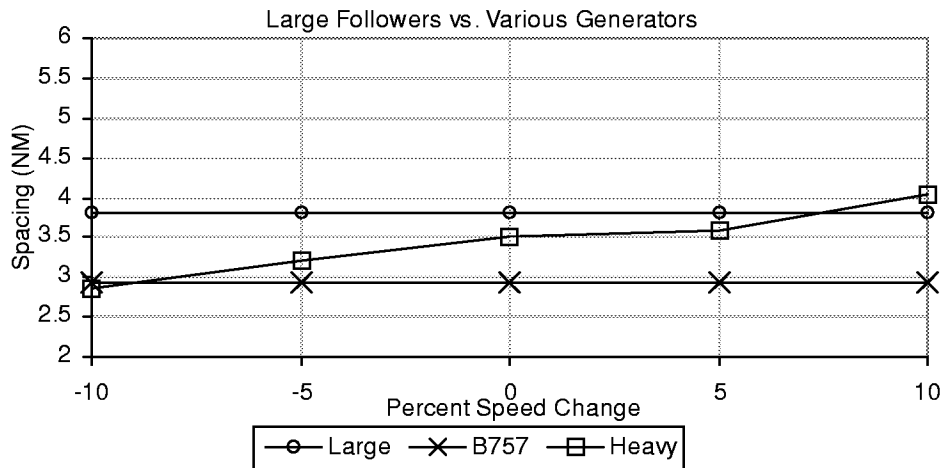
Figure 11b – Spacing changes due to uncertainty in aircraft approach speeds. (Windy, High TKE, Unstable)
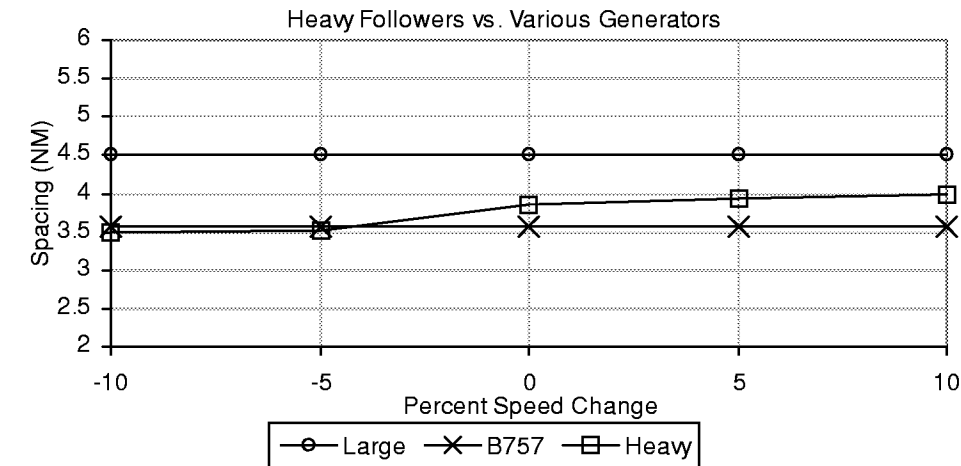

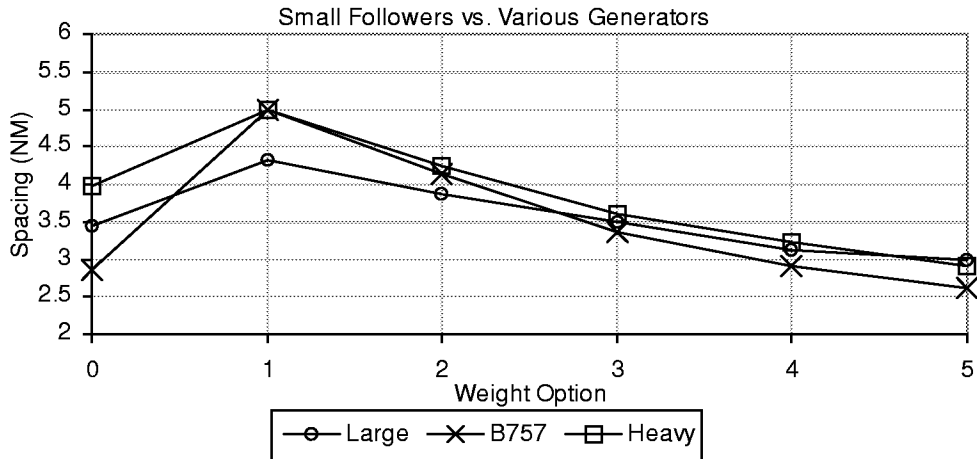*Figure 11c – Spacing changes due to uncertainty in aircraft approach speeds. (Windy, High TKE, Unstable)*

Figure 12a – Spacing changes due to uncertainty in approach aircraft weight. (Windy, High TKE, Unstable) Refer to table 5 for weight options.
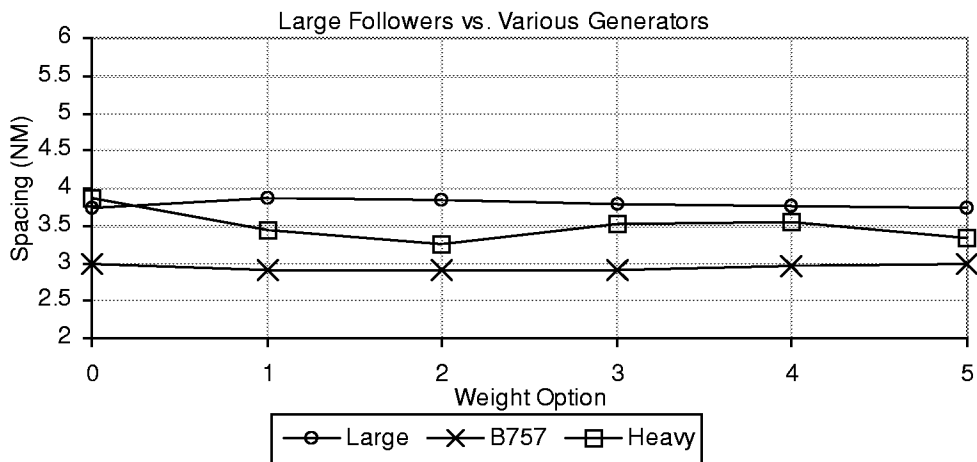

Figure 12b – Spacing changes due to uncertainty in approach aircraft weight. (Windy, High TKE, Unstable) Refer to table 5 for weight options.
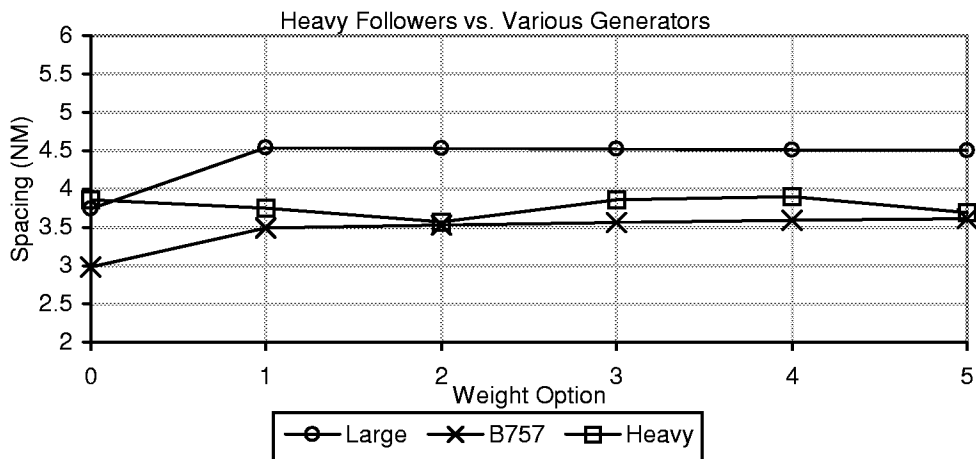

Figure 12c – Spacing changes due to uncertainty in approach aircraft weight. (Windy, High TKE, Unstable) Refer to table 5 for weight options.
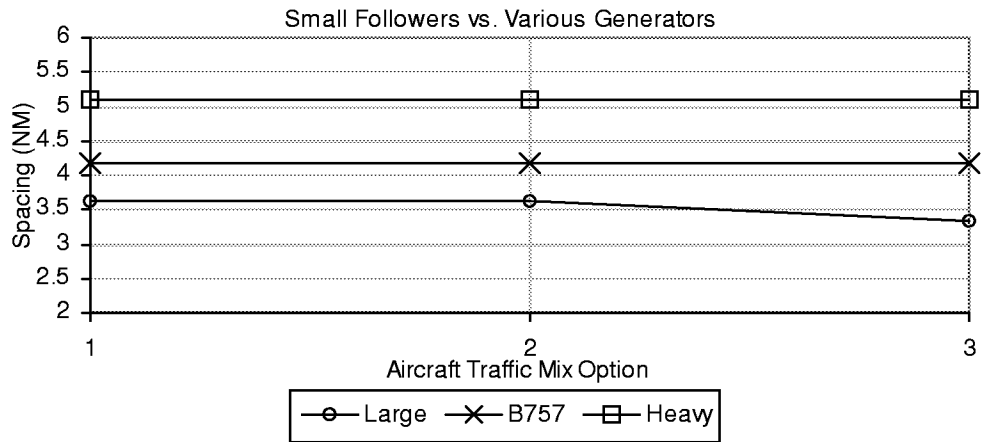
Figure 13a – Spacing changes due to uncertainty in approach aircraft traffic mix. (Calm, Low TKE, Unstable)
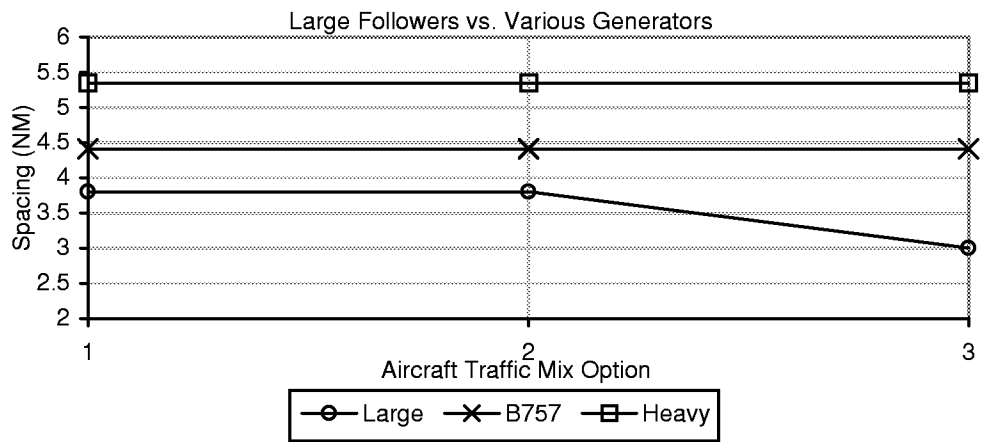

Figure 13b – Spacing changes due to uncertainty in approach aircraft traffic mix. (Calm, Low TKE, Unstable)
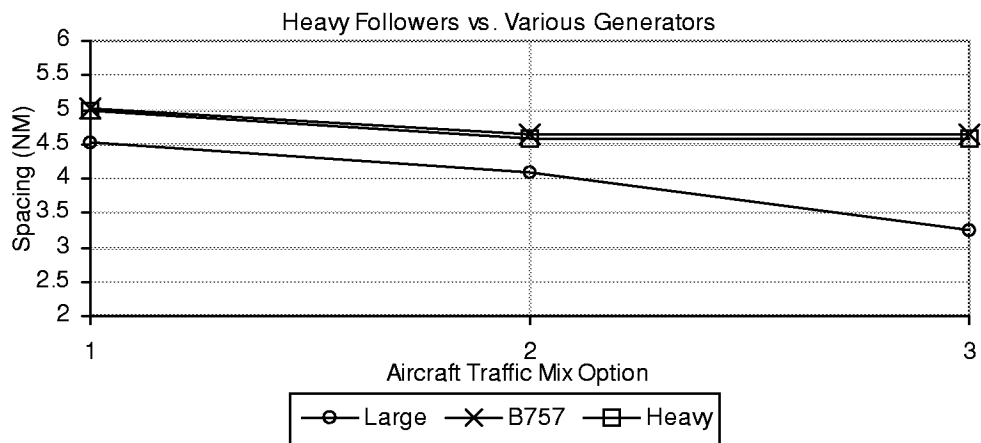

Figure 13c – Spacing changes due to uncertainty in approach aircraft traffic mix. (Calm, Low TKE, Unstable)

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13. ABSTRACT *(Maximum 200 words)*

A study has been performed on a computer code modeling an aircraft wake vortex spacing system during final approach. This code represents an initial engineering model of a system to calculate reduced approach separation criteria needed to increase airport productivity. This report evaluates model sensitivity toward various weather conditions (crosswind, crosswind variance, turbulent kinetic energy, and thermal gradient), code configurations (approach corridor option, and wake demise definition), and post-processing techniques (rounding of provided spacing values, and controller time variance).

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