

A DEPARTURE WAKE VORTEX MONITORING SYSTEM: CONCEPT AND BENEFITS*

Timothy J. Dasey

**Lincoln Laboratory
Massachusetts Institute of Technology**

Abstract

This paper highlights a concept for an automated departure wake vortex separation system. Wake vortex research has focused on reducing aircraft separations on arrival to airports, but in many cases, the departure queues for certain runways are more severely limiting to airport capacity than are arrival constraints. A departure system has the advantages that it could be used in all weather conditions and it is technically simpler because there is no longer a requirement for a 30-minute to several hour weather forecast in order to take advantage of the reduced spacings. This paper examines the technical requirements of such a system, and defines a concept for implementation of the system. An attempt is made to begin to quantify the dollar benefit from a departure system, and the obstacles to implementation of the system are discussed.

Introduction

Aircraft wake vortices are strongly counter-rotating tubes of air that are generated from aircraft as a consequence of the lift on the aircraft. The safety concern of wake vortices, particularly when lighter aircraft are following heavy planes, has caused

the Federal Aviation Administration (FAA) to enact minimum separation requirements during the arrival and departure phases of flight. Any movement toward increasing air traffic efficiency, such as concepts toward free-flight, must address increasing runway capacity if they are to be fully effective. Decades of past wake vortex measurements clearly show that current wake vortex separations are overconservative in many weather conditions, and that adapting the separations to the current weather state could safely reduce these separations.

Wake separations are defined according to the weight categorization of the leading and following aircraft. The separation matrix that has been defined is shown in Table 1. Notice that the B757 (previously the heaviest aircraft in the Large category) is now declared as a separate category as a leader. The three-mile separations in the matrix are constrained by radar separation criteria rather than wake vortex limits, and is reduced to 2.5 miles at some facilities. The separations in Table 1 are required at the arrival threshold in IFR. On departure, aircraft in the large and small categories must wait two minutes behind a B757 or heavy departure. As an alternate they may apply the arrival separation criteria on departure, with the exception that there is no specific requirement for small aircraft following large aircraft.

* Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.

Follow\Lead	Small	Large	B757	Heavy
Small	3	4 (3)	5	6
Large/B757	3	3	4	5
Heavy	3	3	4	4

Table 1. Wake vortex separation criteria. Small aircraft are less than 41,000 lbs., heavy aircraft are all planes larger than a B757. The number in parenthesis is used on departure if the facility decides to use this separation matrix in lieu of a two-minute wait behind a B757 or heavy.

Wake vortex research in the US has concentrated on alleviation of the wake constraints on arrival. The current research focus is the Aircraft Vortex Spacing System (AVOSS), which is a NASA Langley Research Center effort toward developing the technology for an automated system for adaptively reducing arrival aircraft wake separations (Hinton, 1996). The technology being developed for AVOSS, in the form of improved physical models of vortex behavior, long-range wake vortex sensor technology, and efficient measurement of relevant meteorological variables, is applicable to both the departure and arrival problems. However, thus far NASA has concentrated on applying this technology only toward the arrival problem.

There are compelling reasons why a departure wake vortex system should be simpler to implement than an arrival system. In order for aircraft to be available to take advantage of any reduced separations, an arrival system needs to provide ATC with information on future wake vortex separation criteria. At a minimum this information needs to be available about 30 minutes prior to aircraft landing, but it is likely that the projected spacing criteria need to be provided one to three hours ahead of time in order to be able to determine the rate of arrivals to the airport. This operational forecasting requirement translates into a technical requirement that vortex behavior be forecast well ahead of time. This requires

- a robust model of vortex behavior, and

- an accurate weather forecasting system that can characterize the wind and turbulence conditions that affect vortex behavior.

Since a departure wake vortex system only needs to indicate when the next departure can safely proceed, this difficult weather forecasting challenge is removed.

The other main advantage that a departure system has is the operational period during which benefits can be achieved. Departure wake separations are applied during both VFR and IFR, whereas arrival wake separations are applied only during IFR periods.

In many situations, current airport capacity in VFR is limited by departure throughput rather than arrival capacity. Officials at Dallas-Ft. Worth (DFW) airport, as an example, cite departure restrictions as the second biggest capacity limiter (behind surface traffic congestion). A previous study of reduced separations standards at O'Hare International Airport (ORD) demonstrated a large benefit with the adoption of reduced wake separation standards on arrival, using an FAA approved airport simulation model (Loney and Goldberg, 1991). However, the increased arrival throughput resulted in increased departure delays (generally due to runway operating plans that require high levels of interaction between arrival and departure control), which reduces the effectiveness of an arrival wake system. This is because of the significant coordination required between arrival and departure traffic at ORD.

In addition to the technical considerations that make a departure system simpler to implement than an arrival system, there are fundamental reasons to believe that wake vortices on departure are less hazardous than on arrival. Wake circulation (a measure of the rotational strength of a vortex) is inversely proportional to airspeed, so that the higher airspeeds on departure will create weaker wakes than on arrival. Furthermore, the recovery capabilities of the aircraft are greater, since the aircraft is at a higher energy state on departure and the steeper rate of climb gives a pilot recovery altitude quickly after takeoff. The most extensive database of wake vortex encounters indicates that arrival encounters comprise about 90% of all reported encounters (Critchley and Foot, 1991).

This paper takes a first cut at quantifying the benefits of an adaptive wake vortex departure separation system and then discusses a concept for the technical organization of such a system. Challenges to implementation of the system are identified.

Departure System Benefits

A first look at quantifying the potential benefits of a wake departure system was accomplished by analyzing delays at Los Angeles International Airport (LAX). LAX was chosen because of the high proportion of heavy and B757 aircraft and the high traffic rate and delay. Data on existing taxi-out delay at LAX was gathered from the Airline Service Quality Performance (ASQP) system, which provides actual versus scheduled times for departure time, wheels-up time, wheels-down time, and arrival time. Commuter and international flights are not included in the database. The analysis was conducted on ASQP data from all of 1996.

Figure 1 shows the distribution of taxi-out times at LAX. For every departure the time between leaving the gate and arriving at the end of the departure queue cannot be reduced by a wake departure system. Also, the time from when the aircraft is cleared for departure and the wheels are up must similarly be discounted. Using Figure 1 and analyzing the distribution by time of day, an attempt was made to determine the average time that an aircraft would take to depart in the absence of a queue of aircraft ahead of it. For LAX this was estimated at 5 minutes.

The ASQP database for LAX contains 90,814 combined hours of taxi-out time. Since this does not include commuter or international flights, the delay hours were extrapolated upward. The percent commuter and international is estimated at 30% (from Southern California TRACON), leading to an estimate of $90,814/0.7 = 129,734$ hours of total taxi-out time for LAX. Subtracting 5 minutes for each aircraft gives 86,999 hours of time waiting in a departure queue.

The strategy employed is to assume that the likelihood of a given leader-follower pair is related solely to the likelihood of each weight category. That

is, the likelihood that any particular aircraft waiting in a departure queue is waiting behind an aircraft in a particular weight category is just the prevalence of that category in the traffic mix. The traffic mix at LAX was taken to be 20% small, 52% large, 10%

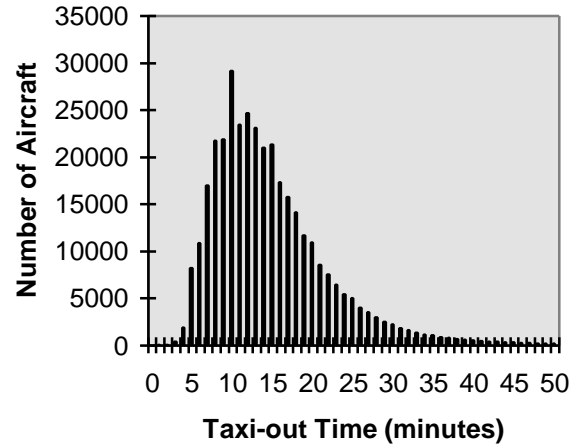


Figure 1. Distribution of taxi-out times at LAX during 1996.

B757, and 18% heavy aircraft, as provided by the Southern California TRACON.

What we would like to know is how much each leader/follower pair contributes to the delay. This is computed as

$$T_{LF} = \frac{P_L P_F S_{LF}}{\sum_a \sum_b P_a P_b S_{ab}} \quad (1)$$

where T_{LF} is the fraction of departure queue time that is consumed because of an aircraft in weight category F following an aircraft in weight category L. P_L and P_S are the probabilities of the leader and follower categories at LAX, respectively, and S_{LF} is the required spacing between category L and F aircraft,

Follow/Lead	Small	Large	B757	Heavy
Small	0.03	0.09	0.03	0.06
Large/B757	0.11	0.28	0.07	0.16
Heavy	0.03	0.08	0.02	0.04

Table 2. Fraction of departure queue time at LAX that is spent waiting for each possible leader/follower combination (T_{LF}).

Time (s)	Fraction of time B747 vortex decays (P_c)	Delay Savings (hours), B
< 60	0.3	3623.2
60 – 70	0.2	1716.3
70 – 80	0.05	254.3
80 – 90	0.25	748.0
90 – 100	0.07	63.0
100 – 110	0.04	18.0
Total	0.91	6422.8

Table 3. Fraction of time that a vortex is clear of the departure corridor for various time periods (Hallock, 1997) and the delay savings found by applying equation 2.

taken from Table 1. The result of this calculation is shown in Table 2. Only the time spent behind a B757 or a heavy (38% of the time) can be reduced, since it is assumed that the 3 mile separations in Table 1 are constrained by factors other than wake vortices (e.g. runway occupancy times, radar separation minima) and cannot be reduced.

The fraction of operating time where it could be expected that separations could be reduced due to wake demise was estimated using operational data collected during the late 1970s and early 1980s by the Volpe Transportation Systems Center (Hallock, 1997, references). They collected the most comprehensive data set on takeoff wake vortices that is available, measuring and analyzing over 30,000 departures from O'Hare International Airport (ORD). The criteria used in this benefit assessment are taken from this vortex data collection from plots of the probability of a vortex living to various ages. The most conservative estimate, using probability curves for B747 vortices, is used.

The delay time saved for each leader/follower pair (B_{LF}) by being able to reduce the wake separations to each of these time intervals c was computed as

$$B_{LF}(c) = P_c \left[\frac{tS_{LF} - c}{tS_{LF}} \right] T_{LF} (D_{total} - NT_{taxi}) \quad (2)$$

which is basically the probability (P_c) that the vortex transported or decayed in the time period c multiplied by the fraction of time saved over the existing spacings S (where τ is the time it takes for the aircraft

to travel one mile and is assumed to be 20 seconds), multiplied by the fraction of time T_{LF} taken by this pairing, times the total taxi time (D_{total}) minus the taxi-time the aircraft are not in the departure queue ($T_{taxi} = 5$ minutes, $N =$ number of aircraft). The delay savings, along with the vortex lifetime criteria used in this calculation, are shown in Table 3.

Airline Operating Costs

The 6422.8 hour departure queue delay savings represents a 7.4% decrease in that delay. According to a FAA LAX Airport Capacity Plan (LAX Airport Capacity Plan Enhancement, 1991), the average airline operating cost (fuel, crew, maintenance) for LAX is \$2,100 per hour. This results in estimated savings of \$13.5M per year in airline operating costs. The maximum benefit that a wake vortex departure system could provide, assuming that any separation times over one minute could be reduced to one minute all of the time, is a 13.3% reduction in taxi-out time and a \$25.4M savings in airline operating costs.

Passenger Time

For departure queue waits greater than 15 minutes (selected because of its relevance to air traffic on-time statistics), it is assumed passenger time then becomes a factor. This study uses a downstream delay multiplier that is due to the passenger time for the aircraft being late for its next flight. The delay savings for the taxi-times greater than 15 minutes is 3629.1 hours, over half of the total departure queue delay savings. The downstream multiplier was determined in a study of downstream delay with ASQP data (Boswell and Evans, 1997), and is taken to be 0.8 times the original delay. That is to say that for delays greater than 15 minutes there are typically .8 minutes of downstream delay for every minute of primary delay. The number of passengers per plane was assumed to be on average 40 people (computed by taking the ratio of the number of emplanements to number of operations at LAX in 1996). The value of a passenger hour is taken as \$45 per hour (FAA Cost, Benefit and Risk Assessment Guidelines, 1996). The passenger delay is then computed to be $1.8 * 3629.1 \text{ hours} * \$45/\text{hour} * 40 \text{ passengers} = \11.75M .

<i>Metric</i>	<i>Benefit</i>
Airline Operating Cost	\$13.5M/year
Passenger Time	\$11.75M/year
Departure Capacity	4.7 aircraft/hr/rwy

Table 4. Summary of the computed benefits of a wake vortex departure monitor for LAX.

Increase in Runway Capacity

The current runway departure capacity can be estimated by finding the average time interval behind a departure. This is computed by summing up the probability of each leader/follower pair (P_{LF}) divided by the time interval required ($S_{LF} \cdot 20$ seconds/mile), and is 51.7 aircraft/hour/runway for the current separations. Using the criteria in Table 3 results in an increase to 56.4 aircraft/hour/runway, an increase in the departure capacity of 9.1%.

The estimated benefits for a wake vortex departure system at LAX are summarized in Table 4.

These computed benefits make some simplifying assumptions that should be mentioned. One assumption is that the taxi-out time is either waiting in a departure queue or taxiing to the queue. This is generally true for LAX, which normally uses one runway on each side of the airport for landing and one on each side for takeoff. However, some small fraction of this time is spent waiting for an incoming arrival that is using the same runway. A quantifiable means of estimating this influence was not available but should be investigated as a refinement to this analysis. The very conservative numbers used for the estimates of vortex lifetimes may counteract this overestimation of benefits. Essentially every wake was assumed to be generated by a B747. The ORD takeoff studies (Hallock, 1997) clearly show that the spacings can be reduced significantly more often behind smaller aircraft, even behind other heavies.

System Concept

The ultimate output of a departure system needs to be information that can be presented to Air Traffic Control (ATC) that will notify them when it is safe for the next departure to proceed. Inputs to the system include flight track and flight plan

information, diagnostic weather information about the local wind and turbulence, and notification from a terminal weather processing system such as the Integrated Terminal Weather System (ITWS) (Evans and Ducot, 1994) of impending wind shifts or storm activity.

As mentioned previously, one of the technical advantages of a departure wake vortex advisory system versus an arrival system is that the technically challenging job of forecasting weather conditions over a 30 minute to several hour time period can be ignored. The only information that is essential is a complete understanding of the wake of a preceding aircraft in the takeoff sequence that can be sent to ATC to aide in their decision process.

There are two possible technical scenarios for this system. In the first possibility, a wake sensor provides direct information to ATC. In this case, there is no predictive component of the system. The difficulty of this implementation is that it reduces operational benefit. The minimum time between aircraft takeoffs with this implementation is the vortex wake lifetime in the sensor coverage area plus the time that the departure takes to generate the wake (assuming that there are no other latencies in the system). If we take as an initial guess that a departure system will need to provide safety coverage until at least a mile after takeoff, then this is over a minute after the aircraft begins its takeoff roll. Most major facilities use the wake arrival separation matrix on departure instead of the two-minute rule, so that the typical time between departures behind heavies or B757s is roughly 80 to 120 seconds (corresponding to 4 to 6 mile separations). You can easily see that even if the wake were to have a short lifetime of only 30 seconds, this type of “reactive” system would not be able to provide significant reductions from existing separations.

A more reasonable system would include a predictive component that would decide ahead of time how the wake from aircraft n in the departure queue would behave and use this information to determine the time required before clearing aircraft $n+1$ for departure. This is the implementation shown in Figure 2. We will later discuss how this very short time prediction (1-2 minute’s prediction time) may be made reliable without it having an in-depth

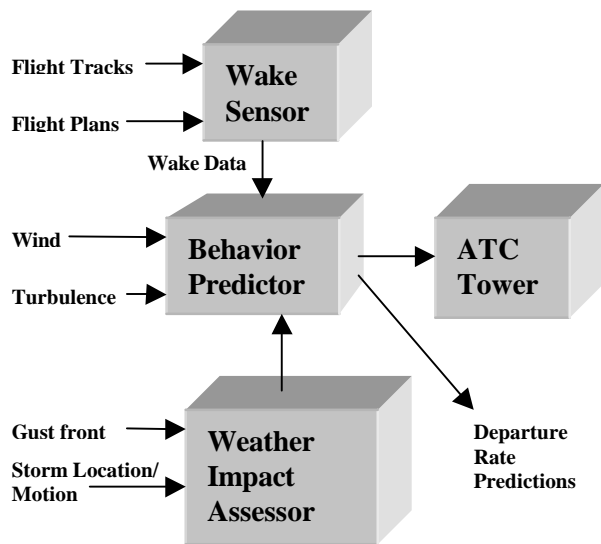


Figure 4. Concept diagram for wake departure understanding of vortex physics.

Each subcomponent of the system is now discussed in more detail.

Wake Vortex Sensor

The most critical portion of a departure system is a wake sensor that can provide real-time information on the position and circulation of vortices of departing aircraft. The sensor, or sensors, must be able to monitor wake vortices near the ground and at higher altitudes at various points along the departure path.

A number of sensing technologies have been used to make wake measurements, including anemometers, lidars, Doppler sodar, and acoustic systems. Doppler lidar systems are the most probable technology for an operational system, since they can be designed to measure vortices out to a kilometer or

Parameter	Specification
Detection range	1 to 2 km
Minimum detectable vortex circulation	75 to 100 m ² /sec
Vortex position and circulation update rate	10 sec
Vortex position accuracy	10 to 20 m
Vortex circulation accuracy	50 m ² /sec

Table 5. Initial proposed sensor requirements.

more, and have the capability of measuring vortex circulation as well as the vortex position. Lidars get their return signal from backscatter from atmospheric aerosols (dust and other pollutants), and so can operate in clear air conditions. They do tend to attenuate significantly in rainy conditions, but since a departure system provides benefit in both VMC and IMC, this should not significantly reduce system benefits.

The output of the wake sensor needs to be the location and circulation of all wakes within the coverage area. Table 5 lists reasonable specifications for a vortex sensor. These are subject to review during system development based on factors such as ATC and pilot feedback, technical capabilities, and more extensive benefit assessment.

Figure 4 shows flight track and flight plan information being provided to the sensor. The flight track data can be used to point the sensor in the area of the initial wake to enhance the scanning efficiency of the instrument. Efficient scanning is important so that frequent updates on the existence of the vortex in the safety corridor can be provided. An automatic vortex detection and tracking algorithm, comparable to the one used by the short-range scientific lidar for the AVOSS project (Dasey and Heinrichs, 1995), can be used. The flight plans provide information on the aircraft and may alternately be used by the Wake Predictor Algorithm.

Wake Behavior Predictor

The wake vortex predictor performs the function of projecting the behavior of the wake vortices of the currently departing aircraft. This projected behavior can then be used to determine when to release the next aircraft. The predictor algorithm is expected to take input from weather sensors in the terminal area and wake vortex behavior of preceding aircraft from the wake sensor.

The short time scale of the wake behavior prediction (1-2 minutes) means that persistence forecast can probably be a very powerful component of the algorithm. If the weather conditions are static and the vortex behavior of preceding aircraft has been consistent with predictions and with each other, then the predictor algorithm at this time can be a simple

prediction of similar behavior. This is a much simpler type of algorithm than the one which must be constructed for a wake arrival system, because a persistence forecast has statistically a much smaller chance of being correct over the 30 minute to several hour prediction interval that is required by such a system.

The weather sensor inputs that will be important information for this algorithm are primarily in the form of wind and turbulence information, the two primary influences on the transport and decay of wakes. It is essential that the wind be provided as a high resolution (< 50 m) vertical profile of horizontal winds, and that the variability of the winds also be adequately captured. This will ensure that the entire range of vortex behaviors is considered in the prediction. It is likely that a long-range lidar can provide the wind information at the range and resolution that is required, but additional information can also be obtained from terminal area Doppler radar systems (TDWR and NEXRAD) and from gridded wind data from the Integrated Terminal Weather System (ITWS).

Additional information from the airport weather impact assessor can be used to help determine when the weather conditions are subject to rapid change or are too variable to be able to predict vortex behavior to the necessary fidelity. It is expected that under these conditions the departure system will default to existing spacing criteria.

Airport Weather Impact Assessment

Terminal weather processing systems such as ITWS will be important in warning a departure monitoring system of potential weather impacts to the airport departure corridors. These changes may take the form of abrupt wind shifts or approaching rain or convective activity. The likely inputs from ITWS are from the gust front detection and forecast, precipitation map, and storm extrapolated position products.

ATC Interface

The operational interface of a departure wake advisory system to ATC is subject to extensive coordination with all of the relevant decision-makers.

The tower local controller is the prime recipient of the information. Informal discussion with controllers has indicated that very simple and easily interpreted information is highly desired. Concepts in the form of a simple “red light/green light” or countdown timers have been discussed and were warmly received. Suggestions of adding additional information in the form of more specific information on the behavior of the vortices were met with less enthusiasm. However, it is possible that the provision of this information on an ancillary display where the Traffic Management Coordinator can review it, or to the pilot community, may enhance user confidence in the system decisions.

Provision of the output of a wake departure system to other ATC personnel has not yet been strongly considered. Extensions to initial departure system capabilities that provide projected departure rates to TRACON and enroute center personnel can easily be envisioned. Such extensions are likely to require the same types of weather forecasts and wake behavior algorithms are being developed for a wake arrival system.

Discussion

This paper has focused on the benefits and technical implementation of an adaptive wake departure monitoring system at major capacity limited airports. Such a system clearly offers high potential reward, and contains technology that can reasonably be developed and implemented in a medium term (3-6 year) time frame.

There are several considerations about the implementation of a departure wake system that should be mentioned. One of the most uncertain aspects of constructing this system is what the requirements will be on the size of the departure corridor where wakes will need to be monitored. Clearly the larger the corridor the higher are the requirements for the wake sensor, in terms of the number of sensors required, the sensor range, and the scanning rate. If, for example, it was determined that the sensor needs to monitor to altitudes of 5,000 ft. or more, then it is much less likely that a suitable sensor can be designed and implemented in a short to medium term research program. Similarly, normal

aircraft divergence on departure creates much less certainty in the future path of a departing aircraft, and thus less certainty that a vortex would be clear of that path. With current takeoff procedures, this clearly limits the system benefits from vortex transport, which is why the benefit calculation in this paper considered only the probability of vortex demise. It is clear that any improvement of the precision of departure paths creates less stringent requirements on adaptive wake vortex systems and probably leads to lower wake encounter rates (Rossow, 1996). More precise departure routes may also be very important in mitigating noise over populated urban areas (Clarke and Hansman, 1997) and these considerations may eventually drive the system in this direction.

Perhaps most importantly, it is critical that pilots and air traffic be closely involved early and often in the design and development of an adaptive wake departure system. User involvement is important in any system development, but is especially important for safety critical systems. Only when all users are comfortable with the capabilities of the system and the criteria it uses will high benefits be realized. With careful design it is likely that this system will substantially increase airport departure capacity, and simultaneously increase airport safety.

References

Boswell, S. B. and J. E. Evans, "Analysis of Downstream Impacts of Air Traffic Delay", Lincoln Laboratory Project Report ATC-257 (available through the National Technical Information Service, Springfield, VA 22161), March, 1997.

Clarke, J. B., and R. J. Hansman, "Systems Analysis of Noise Abatement Procedures Enabled by Advanced Flight Guidance Technology", 35th Aerospace Sciences Meeting, AIAA-97-0490, Jan. 1997.

Cost, Benefit, and Risk Assessment Guidelines for R,E&D Investment Portfolio Development (prepared by the Operations Assessment Division, DTS-59, Volpe Transportation Systems Center for the Program Analysis and Operations Research, ASD-400 and Research Division, AAR-200 of the Federal Aviation Administration), November, 1996.

Critchley, J. B. and P. B. Foot, "UK CAA Wake Vortex Database: Analysis of Incidents Reported Between 1972-1990", Proc. of the Aircraft Wake Vortices Conference (available through the National Technical Information Service, Springfield, VA), Vol. 2, 8-1, Oct. 1991.

Dasey, T. J. and R. Heinrichs, "An Algorithm for the Recognition and Tracking of Aircraft Wake Vortices with a Continuous Wave Coherent Laser Radar", in Coherent Laser Radar, Vol. 19, 1995 OSA Technical Digest Series (Optical Society of America, Washington, DC), 186-189, 1995.

Evans, J.E. and E. R. Ducot, "The Integrated Terminal Weather System (ITWS)", Lincoln Laboratory Journal 7(2): 449-474, 1994.

Hallock, J., "Differences Between Landing and Takeoff Wake Vortices", Proc. of the International Wake Vortex Meeting, Ottawa, Ontario (Transport Canada Publication TP 13166), p. 81, Dec. 1997.

Hinton, D. A., "Aircraft Vortex Spacing System (AVOSS) Conceptual Design", NASA Technical Memorandum 110184, NASA Langley Research Center, Hampton, VA, 1995.

Loney, M. R. and D. F. Goldberg, "The Benefits of Reduced Separation Standards at Chicago O'Hare International Airport", Proc. of the Aircraft Wake Vortices Conference (available through the National Technical Information Service, Springfield, VA), Vol. 2, 29-1, Oct. 1991.

Los Angeles International Airport Capacity Enhancement Plan (prepared jointly by the US Department of Transportation, Federal Aviation Administration, the City of Los Angeles Department of Airports, and the airlines and general aviation serving Los Angeles), available through the FAA Office of System Capacity, or at www.asc.faa.gov, 1991.

Rossow, V. J., "Wake-Vortex Separation Distances when Flight-Path Corridors are Constrained", J. Aircraft 33(3): 539-546, 1996.