AD-A175 957 A CONCEPT FOR USING MULTIPLEGGLIDE SLOPE ANGLES FOR WAKE VORTEX AVOIDANCE (U) MITRE CORP MCLEAN VA J N BARRER NOV 86 MTR-86W144 FAA-DL5-86-3 1/1

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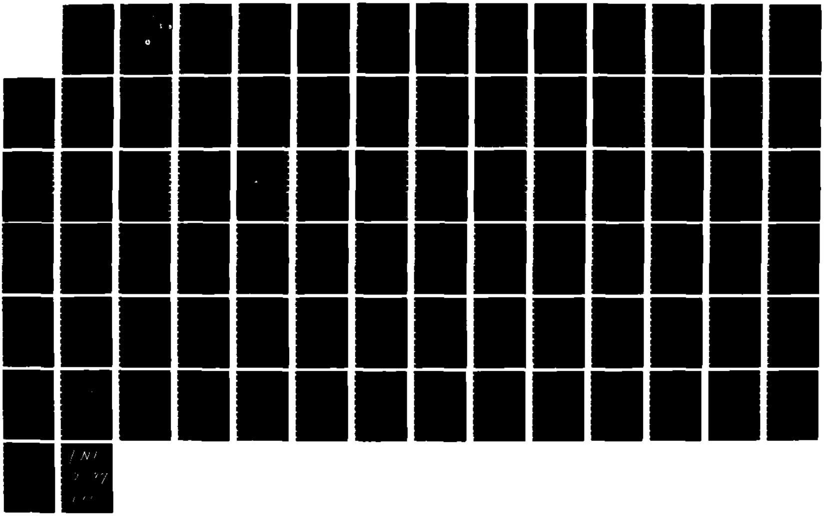

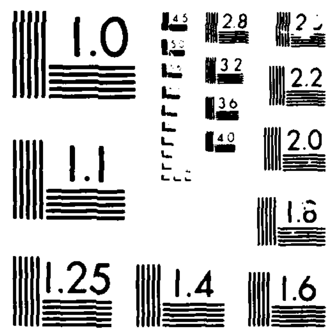
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Report No. FAA-DL5-86-3 MTR-86W144

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AD-A175 957

A CONCEPT FOR USING MULTIPLE GLIDE SLOPE ANGLES FOR WAKE VORTEX AVOIDANCE ON PARALLEL IFR APPROACHES

DR. J. N. BARRER

The MITRE Corporation
McLean, Virginia 22102

NOVEMBER 1986

Document is available to the U.S. public through
the National Technical Information Service
Springfield, Virginia 22161

Prepared for
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
OFFICE OF SYSTEMS STUDIES AND COOPERATIVE PROGRAMS
Washington, D.C. 20591

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-DL5-86-3	ADA175957	

4. Title and Subtitle	5. Report Date
A Concept for Using Multiple Glide Slope Angles for Wake Vortex Avoidance on Parallel IFR Approaches	November 1986
	6. Performing Organization Code
7. Author(s) Dr. J. N. Barrer	8. Performing Organization Report No. MTR-86W144
9. Performing Organization Name and Address The MITRE Corporation 7525 Colshire Drive McLean, Virginia 22102	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFA01-84-C-00001
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Office of Systems Studies & Cooperative Programs Washington, D.C. 20591	13. Type of Report and Period Covered 14. Sponsoring Agency Code ADL-5

15. Supplementary Notes

16. Abstract

For parallel runways separated by less than 2500 feet, the longitudinal separation between aircraft on adjacent approaches must be maintained at the same distance as if the aircraft were on a single runway. The hazard associated with trailing wing tip vortices is the major hindrance to reducing separation distances during instrument approaches. This report shows how separations can be safely reduced on closely spaced parallel runways. The analysis exploits the use of staggered runway thresholds, multiple glide slope angles, and wind measurement devices to ensure vortex avoidance. The analysis is applied to Denver Stapleton International Airport.

17. Key Words	18. Distribution Statement
ATC Procedures, Parallel Runways, Wake Vortex, MLS.	**Available to the Public through the National Technical Information Service, Springfield, Virginia 22161.**

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**		

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PREFACE

The first version of this report was published in September 1981 as MITRE Working Paper WP-81W520. The author wishes to thank Dr. R. M. Harris and Dr. A. N. Sinha for their assistance in preparing that report. In addition, Dr. A. L. Haines carefully reviewed that version in 1982 and suggested that the Denver example be extended by considering the use of a lower glide slope intercept altitude for the heavier aircraft. This allowed the use of a 3.7 degree glide slope rather than a 4.5 degree glide slope. That analysis has been included in this report.

Since 1982, progress has been made in acquiring the Microwave Landing System (MLS) as the replacement for the Instrument Landing System (ILS). The use of MLS's ability to allow cockpit-adjusted glide slope angles makes the application of this wake vortex avoidance procedure easier to implement. Consequently, there has been renewed interest in this concept.

EXECUTIVE SUMMARY

For parallel runways separated by less than 2,500 feet, the minimum radar separation standards between aircraft on adjacent approaches are the same as if the aircraft were on the same approach (3, 4, 5, or 6 nmi). The problem of avoiding wake vortices has been a major hindrance to reducing minimum separation distances on closely spaced parallel runways during instrument meteorological conditions. If diagonal separations could be reduced to 3 nmi or less, substantial increases in airport capacity during Instrument Flight Rule (IFR) conditions could be achieved.

Equipment that can lead to detection, and avoidance or alleviation of vortices has not yet completed development; in the interim, operational solutions to the problem are being considered. This analysis develops a procedure to determine whether minimum separations can safely be reduced at specific sites. It involves a worst-case analysis using present, accepted knowledge of vortex behavior, along with aircraft performance, runway geometry and wind directions. Simple logic is employed to show that under certain meteorological conditions, vortices can be avoided at separation distances of 3 nmi or less with the leading heavy aircraft on one runway and the trailing small aircraft on the closely spaced parallel runway. The results are site dependent and care must be employed in making generalizations. The primary contribution of this report is to show that significant results can be obtained if a site specific solution is sought rather than a global solution to the problem.

Wake vortices are generated by all aircraft; heavy aircraft generate strong vortices that pose a hazard for lighter aircraft. The two wing tip vortices sink below the flight path of the aircraft and slowly decay to a harmless condition. If they come within 200 feet of the ground before they decay, they separate and move in opposite directions and move slightly upward (a phenomenon called "vortex bounce"). This poses a hazard to adjacent aircraft less than 300 feet above the ground. This area, called the "ground effect" region, occurs near the runway threshold for the parallel runways under consideration. A crosswind can transport the vortices at a higher velocity than they normally move, so this must be incorporated into the avoidance procedure.

The principles behind this analysis are that (1) keeping a light aircraft high on its approach will keep it above the vortex of the aricraft it is following; (2) a crosswind in the right direction can prevent vortices from drifting across an adjacent approach and; (3) sufficient longitudinal separation will allow the vortices to decay to a harmless level. The wake vortex avoidance procedure is illustrated in Figure ES-1. The two runways are separated by a distance D that is less than 2,500 feet and the thresholds are staggered by a distance S. The closer runway is used for aircraft that generate vortex hazards trailing

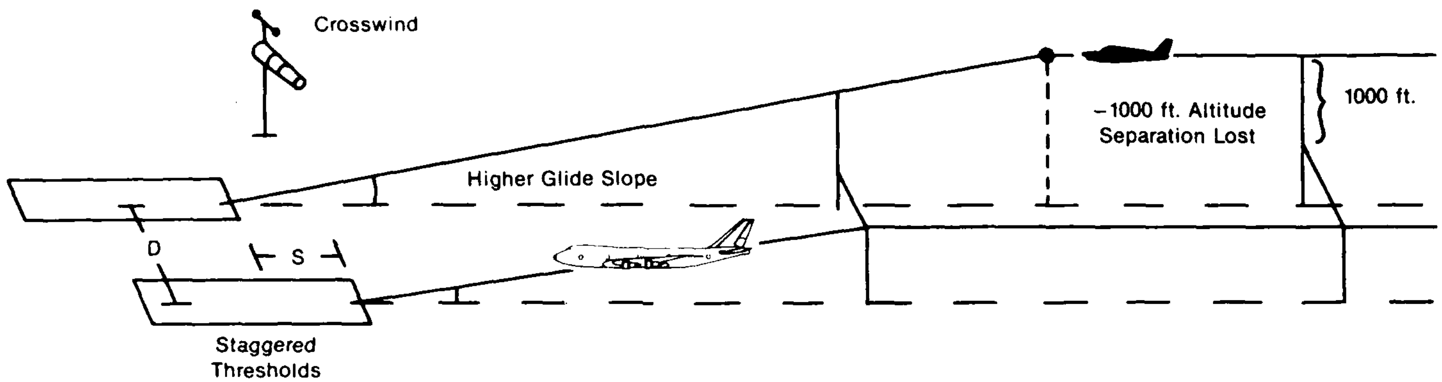

FIGURE ES-1
CONCEPTS FOR OPERATIONAL SOLUTIONS
TO THE PROBLEM OF VORTEX SEPARATIONS

more than 2 miles behind them. Lighter aircraft are assigned to the distant runway. The aircraft are turned on to their localizers in the usual manner for parallel operations using 1,000 foot vertical separation, in this case with the smaller aircraft above the larger one. The glide slope angle of the runway with the staggered threshold is set at a higher angle than the normal 3 degrees used on the near runway. This higher angle together with the staggered thresholds has the combined effect of keeping the smaller aircraft above the flight path and the wake vortex of the larger aircraft. It is necessary to measure the crosswind component to ensure that the vortex hazard generated near the ground by the heavier aircraft can be prevented from drifting towards the smaller aircraft. When the higher glide slope angle is less than 4.4 degrees and the stagger distance is less than 4600 feet, it may be necessary to measure the crosswind component up to 10 miles from the threshold to ensure that it does not drift towards the lighter aircraft.

This report performs a thorough analysis of the interactions between runway stagger, glide slope angles, and crosswind conditions to show what is required to safely reduce the diagonal separation requirements during IFR closely spaced dependent parallel operations. This analysis can be used to analyze any pair of runways.

Denver Stapleton International Airport was chosen as an example to illustrate the use of this analysis. As shown in Figure ES-2, the runways 35R and 35L are separated by 1600 feet and their thresholds are staggered by a distance of 5800 feet. The analysis shows that there are two principal alternatives; one is to leave both glide slope angles at the current 3 degrees and the other is to raise the glide slope on 35R only to 3.7 degrees or greater. The large stagger distance, peculiar to Denver, causes the approach path of 35R to be above that of 35L even when the glide slope angles are the same; other airports would not be able to use a 3 degree glide slope on both runways.

In the case in which both glide slope angles are 3 degrees, the crosswind component would have to be monitored at all points up to 9.5 nmi from the threshold to ensure that there was at least a 3 knot crosswind from right to left (East to West). If the glide slope angle of runway 35R were to be raised to 3.7 degrees and the glide slope intercept altitude on 35L were lowered to 1500 above ground level, then the analysis indicates that the vortex hazard would be eliminated on 35R as long as the aircraft were landing into a headwind or had a tailwind of less than 4 knots. In addition, wind measurements would only be required in the ground effect region within a mile of the threshold of 35R and below 300 feet.

There are some remaining questions that require further analysis. The problem of vortex avoidance is greatly simplified if the glide slope on one of the runways can be increased to 4.4 degrees, because an aircraft using that glide slope will remain above the vortex hazard during all but

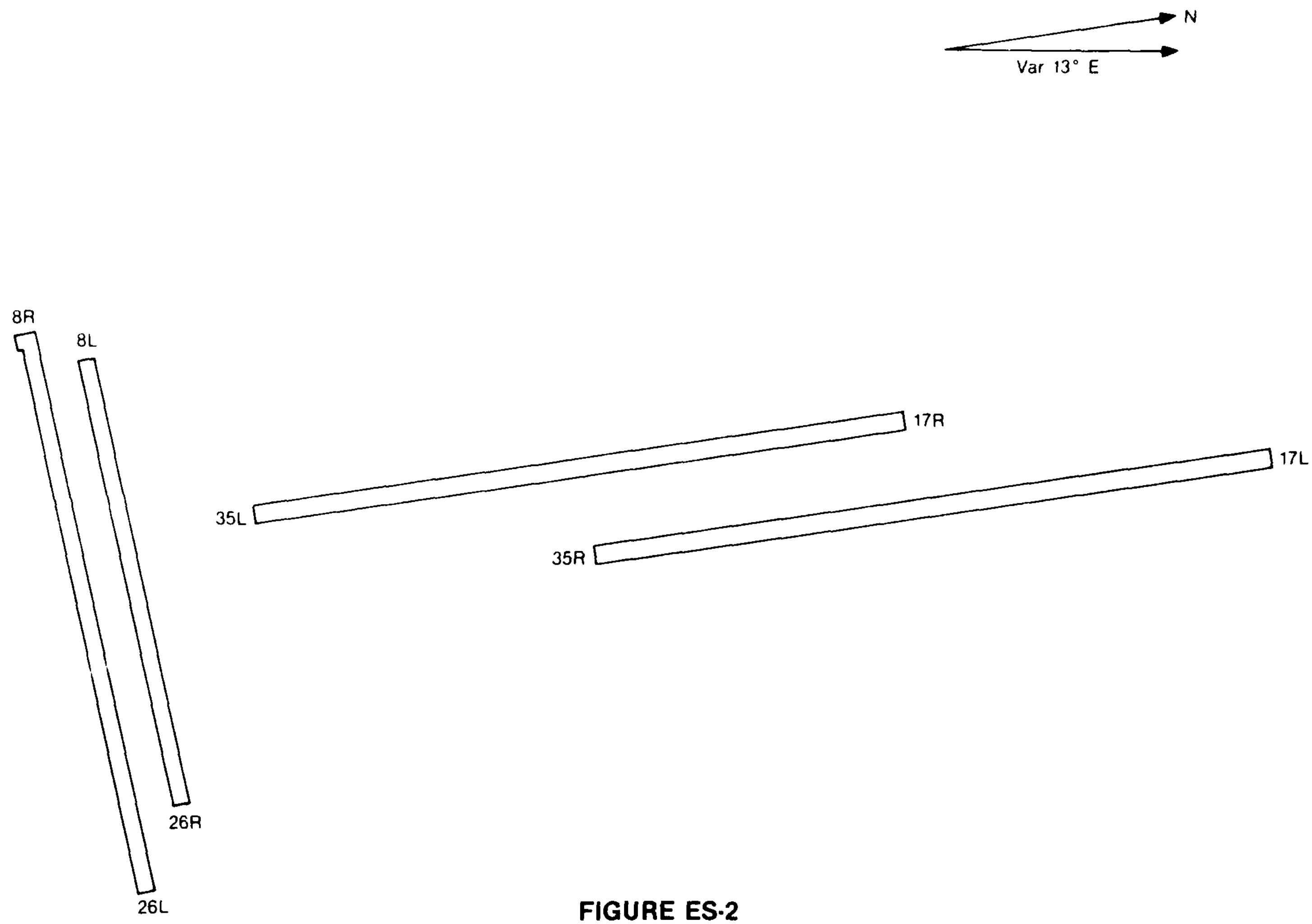

FIGURE ES-2
RUNWAY LAYOUT OF DENVER STAPLETON INTERNATIONAL AIRPORT

the last mile of its approach where a crosswind is required for vortex avoidance. If the glide slope angle is less than 4.4 degrees wind measurements may be required up to 10 miles from the threshold. However, some of the larger aircraft cannot fly an approach at such a steep angle, limiting the type of aircraft that can normally use the runway with the higher glide slope. In addition, this means that if a 4.4 degree glide slope were the only approach available on that runway, the airport would have no instrument approach for heavier jets in the event that the 3 degree glide slope on the other runway experienced an outage. There are ways to solve this problem (e.g., use of MLS), but each needs further consideration with regard to operational requirements, equipage, potential benefits, and costs.

The second question concerns wind measurement devices. If the glide slope angle cannot be increased to 4.4 degrees on the second runway, wind measurements may be required up to a distance of about 10 nmi from the runway thresholds. Further analysis is required to determine what kinds of wind measuring equipment can be used. There are operational benefits which result from using the shallower glide slope but these are offset by the cost of measuring winds at greater distances from the airport. A higher glide slope reduces the wind measuring requirements, but may prohibit some aircraft from using the approach.

In summary, use of a high angle glide slope (3.7 to 4.4 degrees) to a staggered touchdown point on a close parallel runway appears to be a feasible, safe, interim solution to the vortex problem at a number of airports. Its applicability depends upon two site-specific considerations:

1. Presence of a close parallel runway with appropriate length and/or stagger,

2. A sufficient population of aircraft that can routinely employ a higher glide slope.

In addition, all sites will require the development of a simple, inexpensive wind measurement device that will provide a one axis (headwind/tailwind) profile over the last 1 nmi of the approach. Once the technical problems are solved (providing multiple glide slopes and wind sensors), operational procedures must be developed that will be acceptable to the controllers and pilots.

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1. INTRODUCTION

1.1 Background

An airfoil which is generating lift also generates a form of turbulence known as a wake vortex. If vortices could be seen they might look like two tornadoes trailing behind each wing tip. The tangential velocities at certain points in the vortex generated by a heavy aircraft (weighing more than 300,000 lbs.) can exceed the control capabilities of any aircraft. A trailing aircraft which encounters one of these vortices cannot maintain a normal flight path. The most dangerous situations occur when an aircraft is caught in a vortex which is close to the ground because there may be insufficient altitude to recover from the vortex encounter.

The increasing congestion at the major airports has prompted the Federal Aviation Administration (FAA) and the users to search for ways to increase airport capacity and hence reduce delay. The most direct method of increasing capacity is to reduce separation distances between aircraft without any degradation of safety. The existing separation standards are designed to assure that aircraft will avoid encountering vortex hazards and this as the limiting factor is reducing the minimums any farther.

Currently, closely spaced parallel runways (less than 2500 feet apart) are treated as a single runway for vortex separation rules. This means, for example, that a small aircraft must remain 6 miles behind a heavy even though they are landing on different runways. Parallel runways separated by more than 2500 feet are safe from any vortex interactions [1]. A single runway can accommodate about 25 arrivals per hour in Instrument Meteorological Conditions (IMC). Dependent parallel operations would allow about a 40 percent increase in arrival capacity. If a safe method can be devised to reduce Instrument Flight Rules (IFR) separations on closely spaced parallel approaches, significant capacity increases may be achieved. An earlier MITRE study [2] computed that the capacity at ten of the twenty busiest airports could be increased by 3 percent to 13 percent if separations could be reduced to 3 nautical miles (nmi).

1.2 Purpose And Scope

This report will confine its attention to closely spaced parallel runways (0 - 2499 feet between centerlines) and will address operational solutions to the problem of wake vortex separations by considering the effects of using multiple glide slope angles, displaced thresholds and runway stagger.

Other programs are looking at alternatives to the vortex separations through vortex detection, prediction, and alleviation systems. While there has been some success in these programs, the potential solutions are not as yet operational. An alternative is to develop operational procedures to avoid hazardous vortex encounters.

1.3 Organization

Chapter 2 provides a description of the principles used to provide wake vortex avoidance: higher glide slopes, crosswinds, and longitudinal separations. Chapter 3 describes the analysis and shows the major conclusions. The details of the analysis are shown in Appendix A which parallels the description in chapter 3. Chapter 4 describes the results of applying the analysis to Denver Stapleton International Airport. Chapter 5 discusses some of the operational problems that must be addressed prior to implementation. Chapter 6 is intended for a technical analyst and describes how to use the analysis at a particular site.

A summary of the abbreviations and symbols used in this report is given in Appendix E. A list of acronyms is listed in Appendix F.

2. OVERVIEW

Wake vortices are disturbances in the air caused by the movement of an airfoil relative to the air. This form of turbulence interacts with other forms of turbulence and with the undisturbed air in a complex manner that is only partially understood [3]. The two vortices generated at the wing tips create a region of turbulence which is hazardous to other aircraft. Enough information is known about this region so that useful information can be derived regarding its rate of transport through an airmass and the rate at which the disturbed air returns to a harmless condition. Reliable upper and lower bounds on the rate of vortex movements and their lifetimes are available from the technical literature [3,4].

In order to facilitate the analysis, a simplified cross section of the wake turbulence is examined. The wing tip vortices are modeled in two dimensions as disks that drop from the wing tips; are transported by the ambient wind, the effect of their interaction with each other and with the ground; and that increase in radius with time. An upper bound, L, is used as the lifetime of a hazardous vortex and the vortices are assumed to be hazardous during the entire interval (0, L). Using the upper and lower bounds on the velocity at which vortices are transported and an upper bound on the lifetime of a vortex, it is possible to define an area within the cross section which could possibly contain the vortex hazard. With that knowledge it is possible to derive sufficient conditions to ensure that a trailing aircraft will not encounter the hazardous region. These conditions are characterized by wind velocities, the runway geometry and separation distances.

The analytical portion of this report (contained in Appendix A) begins with a description of how wing tip vortices are transported and how they decay. The decay rate is deduced from the current Air Traffic Control (ATC) separation rules and is assumed to be independent of the transport rate. This is a conservative assumption because studies indicate that the rate of decay increases with the rate of transport. The runway geometry is then defined by introducing appropriate notation to describe the relationship of the flight paths of the aircraft. The flight path is divided into three stages that are defined by the runway geometry. A detailed discussion then shows what conditions are required to ensure vortex avoidance during each of the three stages.

There are three arguments used to show that a given separation rule is safe. These are illustrated in Figure 1. First, the trailing aircraft can be shown to be safe if the runway geometry, determined by the glide slope angle and length of the threshold displacements, positions the aircraft sufficiently high above the vortex hazard. Second, the crosswind component can be determined that is sufficient to transport the hazardous

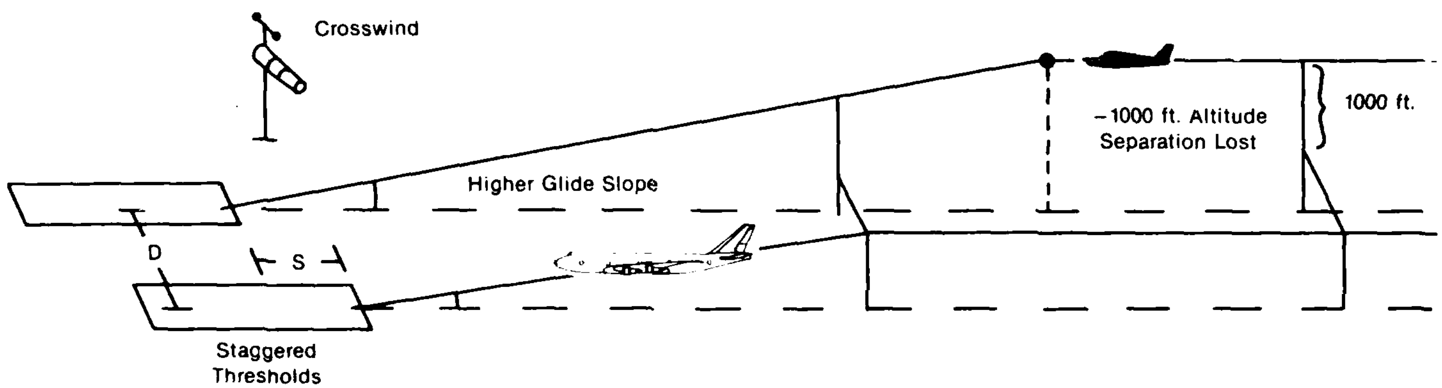


FIGURE 1
CONCEPTS FOR OPERATIONAL SOLUTIONS
TO THE PROBLEM OF VORTEX SEPARATIONS

region (containing the vortices) away from the path of the trailing aircraft. The required component is a function of the distance, D, between the two runways. Finally, a separation distance can be computed which ensures that the time required for the trailing aircraft to reach the hazardous region exceeds the lifetime of the vortex hazard. These three arguments are referred to as *altitude, crosswind,* and *harmless encounter,* respectively. During a typical instrument approach, the trailing aircraft could be above or below the flight path of the leading aircraft at different times. One or more of the three arguments are used to establish vortex hazard avoidance, depending on the relationship of the two flight paths.

3. ANALYSIS

A detailed derivation of the following wake vortex equations is given in Appendix A. This section provides a simplified discussion and summary. The analysis consists of three parts: a brief discussion of wake vortices, a description of the runway geometry, and the derivation of the conditions for safe operations at reduced spacings.

3.1 The Motion of Wake Vortices

Figure 2 illustrates the motion of wing tip vortices near the ground and at higher altitudes. An aircraft having wingspan, b, produces a pair of vortices. The pair of vortices interact with each other inducing a downward velocity, V_d. The vortices descend at this rate which remains constant for several seconds, then decreases to zero at a distance of at most 1000 feet below the height at which they were generated [3].

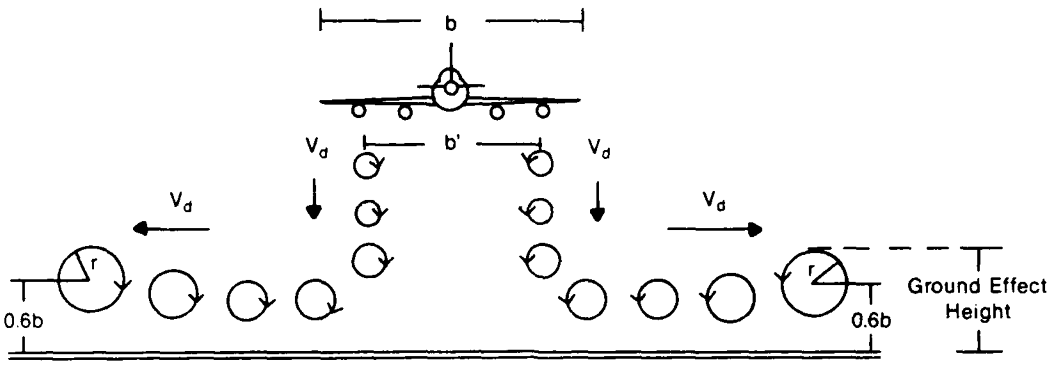
If the pair of vortices descends to a height above ground equal to about b/2 (called the ground effect region), their interaction with the ground and with each other causes them to move in a horizontal direction, away from each other. It is important to note that the motion of the vortices relative to the airmass is caused by the mutual interaction of the vortex pair rather than other forces such as gravity. The horizontal velocity of each vortex is at most, V_d. This model neglects atmospheric instabilities and certain other factors involved in vortex decay. However, it is certain that V_d provides an upper bound on the horizontal velocity of the vortices as they begin to separate. The vortices remain at a constant altitude as they move in the horizontal plane for a certain distance, then they begin to rise to a height of about 0.6b but not more than b. This phenomenon is referred to as "vortex bounce". The vortices also expand in size as they age, achieving a radius of between 50 and 75 feet. The vortex continues decaying and by using the current FAA separations standards, it is possible to derive an upper bound on the life of a vortex hazard.

Both experimental and theoretical arguments support the following conclusions.

1. The lower and upper bounds on vortex velocity, V_d, are 2 feet/second (V_ℓ) and 13 feet/second (V_u).

2. The ground effect region is below 300 feet Above Ground Level (AGL).

3. The FAA 6 nmi separation rule at the threshold implies that the maximum lifetime of a vortex hazard (for a small aircraft at 90 kts. behind a heavy aircraft) is 180 seconds in ground effect. The 5 nmi rule on approach implies that the lifetime is 150 seconds out of ground effect.



V_d = Transport velocity of vortex in motionless air
b = Wingspan
r = Maximum radius of vortex
b' = Initial separation between vortices

FIGURE 2
THE MOTION OF WAKE VORTICES

These bounds are very conservative. The approach used in the analysis is to determine conservative bounds for all of the parameters and avoid the use of statistical arguments to establish safe minimum separations.

3.2 Runway Geometry

A typical parallel runway configuration is shown in Figure 3. There are a few assumptions implied by the figure. First, the runway labeled RW_1 is defined as that which has its threshold closer to the outer marker. Consequently, the stagger distance, S, is always non-negative. Also, there is an assumption that the heavy aircraft is using runway 1. The location of the outer marker is not pertinent to the analysis.

The angle shown for each approach path represents the nominal glide slope, α_i, plus or minus the maximum vertical error, ε. In the worst case, the heavy aircraft will fly at too high an angle, $\alpha_1 + \varepsilon$, and the trailing aircraft will fly at too low an angle, $\alpha_2 - \varepsilon$. In this way, vertical navigation errors have been incorporated into the analysis.

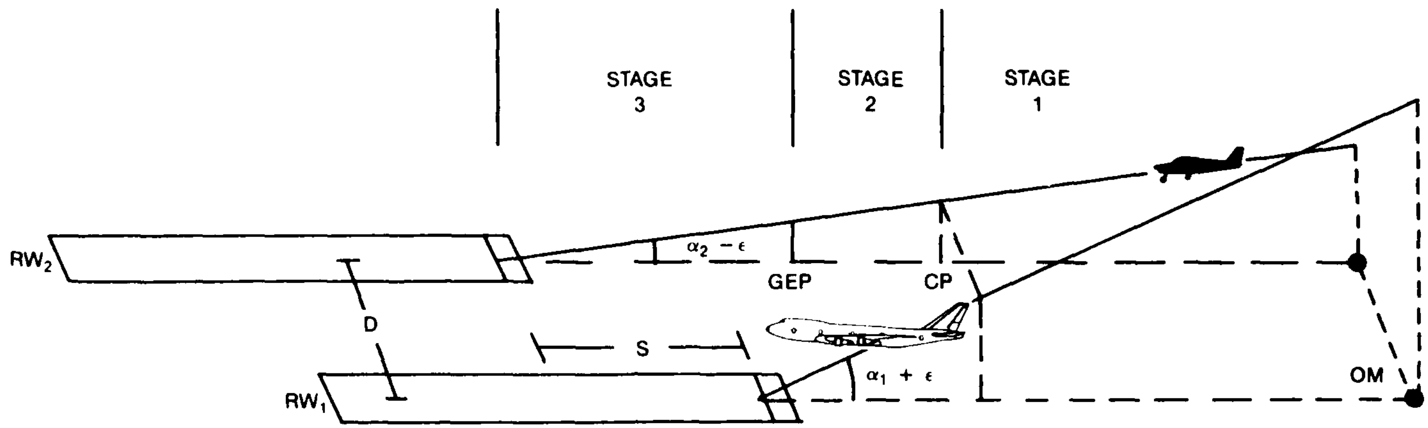
The points labeled Ground Effect Point (GEP) and Crossover Point (CP) have no operational significance but are useful for the analysis. At the point GEP, the lower limit of the flight path of the trailing aircraft is 300 feet AGL. At the point CP, the lower boundary of the trailing aircraft's path is at the same altitude as the upper boundary of the leading aircraft's path.

The approach path of the trailing aircraft is divided into three stages and conditions for safety are derived for each stage. Stage 1 is that portion of the approach prior to the point CP in which vertical separation is less than 1000 feet. Stage 2 is the portion between the points CP and GEP. Stage 3 is from the point GEP to touchdown. For a given combination of runway and flight path geometry (S, D, α_1, α_2) it is possible that GP does not exist. In this case, only stages 1 and 2 will be present.

3.3 Criteria for Avoiding Vortex Hazards

The analysis identifies wind conditions for each of the three stages that assure safe operations at the desired reduced spacings. By combining the requirements of the applicable stages, those wind conditions are computed that ensure safety from vortex hazards at reduced separation for the entire flight path.

In Stage 1, the trailing aircraft is less than 1000 feet below the path of the leading aircraft. The only way to protect the aircraft is to make sure that either (1) the crosswind prevents the vortices from traveling toward the trailing aircraft's path, (2) the wind transports the



D	—	Distance Between Runway Centerlines
S	—	Distance Between Thresholds
$\alpha_1 + \epsilon$	—	Upper Limit for Leading Aircraft
$\alpha_2 - \epsilon$	—	Lower Limit for Trailing Aircraft
CP	—	Crossover Point (May Not Exist)
GEP	—	Ground Effect Point (Between or Beyond Both Thresholds)

FIGURE 3
FLIGHT PATH GEOMETRY

vortices beyond the trailing aircraft's path before it arrives, or (3) the separation is large enough so that the vortex has decayed to a harmless condition before the arrival of the trailing aircraft.

During Stage 2, the trailing aircraft is above the flight path of the leading aircraft. The danger is that a sufficiently strong tailwind will carry the vortices forward at a faster rate than that at which they are sinking, thereby creating a hazard *above* the flight path of the leading aircraft. A sufficiently strong crosswind could then transport them towards the trailing aircraft and possibly creating a hazard. The required tailwind component which will prevent such a hazard can be computed.

During Stage 3 the vortices may "bounce" because they are generated at a point which is less than 300 feet AGL for all aircraft. The trailing aircraft must be protected all the way to its touchdown point which is beyond that of the leading aircraft. This stage is more complicated to analyze because the arguments change depending on whether the point GEP falls beyond the two touchdown points (referred to as case 1) or between them (case 2). In case 1 a sufficiently strong headwind and crosswind will prevent the vortices from crossing the path of the trailing aircraft. In case 2, where the GEP is between the two thresholds, only a tailwind and crosswind could transport the vortex forward and across the path of the trailing aircraft. The value of the maximum allowable tailwind can be computed.

A detailed discussion of the analysis is given in Appendix A. Table 1 summarizes the wind equations required for vortex avoidance and Table 2 summarizes the notation used. All of the equations represent bounds on certain wind velocities (V_c - crosswind, V_t - tailwind, V_h - headwind) which are requirements for safe operations. Each equation implies a wind requirement for a given stage. If a subset of wind requirements protects each of the three stages, that collection of conditions protects the entire approach. For example, if the wind conditions satisfy equations 1 and 4, all three stages of the approach are protected and a small aircraft on runway 2 can follow a heavy aircraft on runway 1. The runway geometry is classified into four configurations depending on the existence of the CP and the position of the GEP (between or beyond the thresholds). It is possible to derive Table 3 (see Appendix A) which summarizes the wind conditions required for a safe approach at reduced separations. The most convenient way to present the result is to graph the conditions for safety on a wind diagram. This will be illustrated by the example shown in section 4.

TABLE 1
SUMMARY OF WIND CONDITIONS FOR VORTEX AVOIDANCE

	STAGE PROTECTED
(1) $V_c < \dfrac{D - \dfrac{b_1 + b_2}{2}}{t_a}$	1, 2
(2) $V_c > \dfrac{D + \dfrac{b_1 + b_2}{2}}{t_e}$	1, 2
(3) $V_t < \dfrac{V_\ell t_e - 100}{\tan(\alpha_1 + \varepsilon)\, t_e}$	2 CP exists
(3a) $V_t < \dfrac{S - \dfrac{100}{\tan(\alpha_2 - \varepsilon)} + \dfrac{300}{\tan(\alpha_1 + \varepsilon)} - \dfrac{300}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \dfrac{V_\ell}{\tan(\alpha_1 + \varepsilon)}$	2 (CP does not exist)
(3b) $V_t < \dfrac{S - \dfrac{100}{\tan(\alpha_2 - \varepsilon)} + \dfrac{A_1}{\tan(\alpha_1 + \varepsilon)} - \dfrac{A_1}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \dfrac{V_\ell}{\tan(\alpha_1 + \varepsilon)}$	2 (CP exists but is operationally not critical)
(4) $V_c < \dfrac{D - \dfrac{b_1 + b_2}{2}}{t_g} - V_u$	3 (Implies 1, 2)
(5) $V_c > \dfrac{D + \dfrac{b_1 + b_2}{2}}{t_e} - V_u$	3 (Implies 1, 2)
(6) $V_t < \dfrac{d_1}{t_g}$	3 (CASE 1)
(7) $V_h > \dfrac{d_2}{t_e}$	3 (CASE 2)
(8) $(V_u + V_c)^2 + V_t^2 < \dfrac{\left(D - \dfrac{b_1 + b_2}{2}\right)^2 + d_1^2}{t_g^2}$	3 (CASE 1)
(9) $(V_c - V_u)^2 + V_h^2 > \dfrac{\left(D + \dfrac{b_1 + b_2}{2}\right)^2 + d_2^2}{t_e^2}$	3 (CASE 2)

(Note: Equations (8) and (9) are second Order Refinements that are Difficult to Implement)

TABLE 2
NOTATION USED IN WIND EQUATIONS

α_i	Glide slope angle of runway i (i = 1, 2)
ε	Vertical navigation error (.7° for ILS)
b_1	Wingspan of leading aircraft
b_2	Wingspan of trailing aircraft
d_1	Distance from GEP to RW1 threshold (case 1)
d_2	Distance from GEP to RW1 threshold (case 2)
D	Distance between runway centerlines
S	Stager distance between thresholds
t_a	Maximum lifetime of a vortex hazard above ground effect (seconds)
t_e	Longitudinal separation (minimum) between aircraft measured in seconds
t_g	Maximum lifetime of vortex hazard when in ground effect crosswind component of wind (from leading to trailing)
V_t	Tailwind component
V_h	Headwind component
V_u	Upperbound on rate of vortex transport in still air
V_ℓ	Lowerbound on rate of vortex transport in still air
V_d	Rate of vortex transport in still air

TABLE 3
WIND CONDITIONS REQUIRED FOR EACH CLASSIFICATION

CLASSIFICATION	CP	GEP	EQUATIONS
I	Exists	Between	(4) or (5) or (1 and 6) or (2 and 6)
II	Exists	Beyond	(4) or (5) or (1 and 7) or (2 and 7)
III	Vanishes	Between	(4) or (5) or (1 and 6) or (2 and 6) or (3 and 6)
IV	Vanishes	Beyond	(4) or (5) or (1 and 7) or (2 and 7) or (3 and 7)

4. APPLICATION TO DENVER STAPLETON INTERNATIONAL AIRPORT

The analysis technique was applied to Denver's Stapleton International Airport (Figure 4). The details of this analysis are provided in Appendix A. Parallel runways 35R and 35L are separated by 1600 feet and the threshold of 35R is staggered 5800 feet beyond that of 35L. Currently, both glide slope angles are 3 degrees. This geometry yields classification II in Table 3. Consequently, from Table 3 the approach is safe at reduced separations if the wind satisfies either equation (4) or (5) or (1 and 7) or (2 and 7).

The region on the wind diagram satisfying these conditions is shown in Figure 5. The horizontal axis represents the crosswind component and the vertical axis represents the headwind component. The "bottle-shaped" figure contains the wind conditions under which current separation rules should be applied. If the wind conditions correspond to a point outside the "bottle" then the diagonal separation between aircraft on adjacent approaches may be safely reduced to 3 nmi. Requiring a crosswind towards the heavy aircraft of at least 4 kts would be a convenient operational rule to ensure that the wind conditions are safe for reduced separations. Wind measurements would be required up to a distance of 9.5 nmi from the threshold to ensure that Stage 1 of the approach is safe.

If the glide slope of the second runway (35R) were increased to 4.5 degrees, the safe region changes to that shown in Figure 6. The implication of the "table-shaped" figure which lies below the zero-headwind axis is that in the presence of a headwind the two runways are vortex independent. In this case knowledge of wind direction would only be required within 1 mile of the threshold to an altitude of 300 feet.

Further analysis (see Appendix A, section A.7) has shown that a glide slope of 3.7 degrees can be used on runway 35R if the glide slope intercept altitude for the heavier aircraft is set at 1,500 feet above ground. This is due to the large stagger (5,800 ft.) between the two thresholds. The stagger causes the crossover point to move outward and occur at the point where the heavier aircraft is at an altitude of about 1,500 feet. If the glide slope intercept altitude is set at 1,500 feet, then the lighter aircraft will be above the heavier one at all points except within 1 nmi of the threshold.

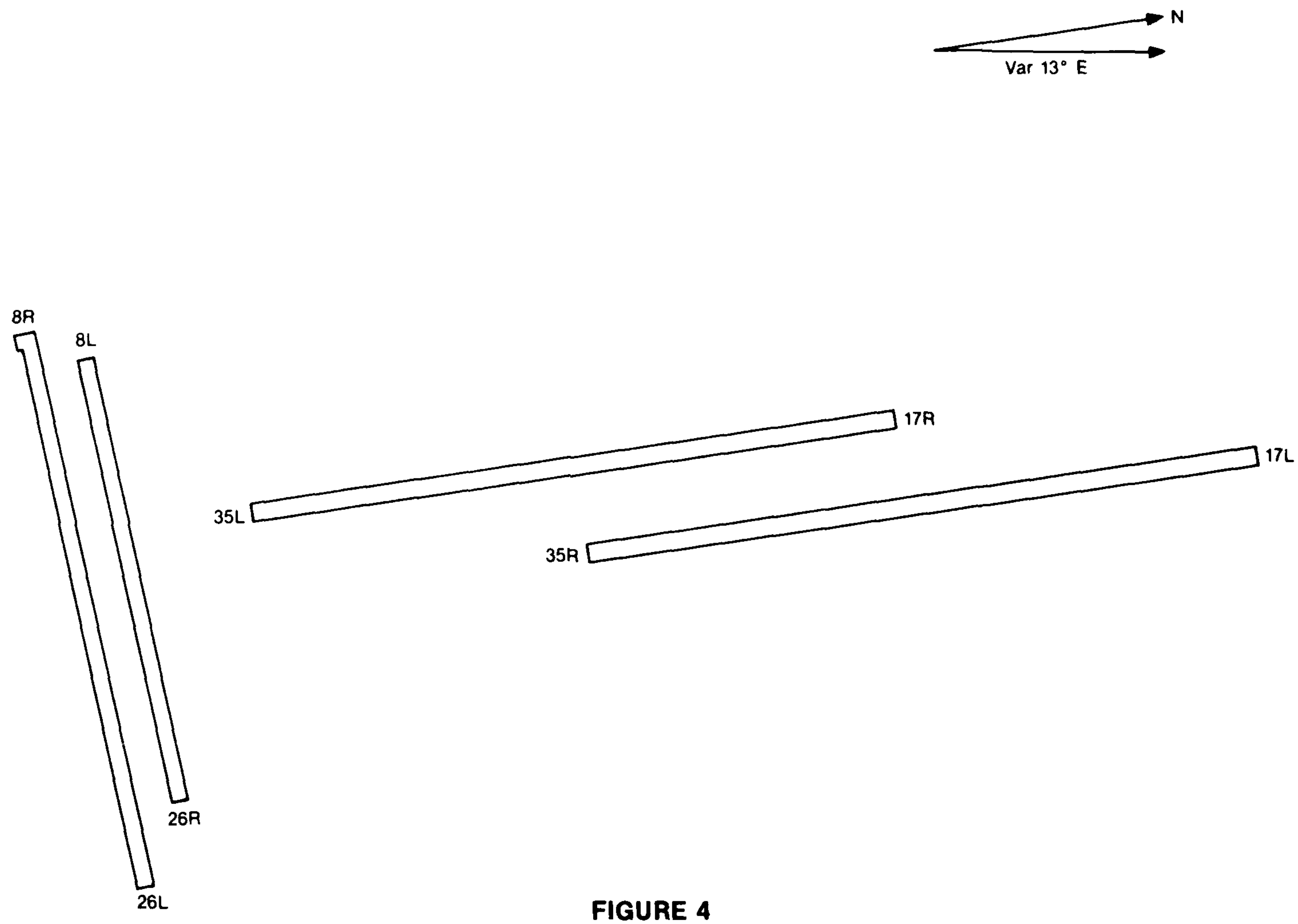
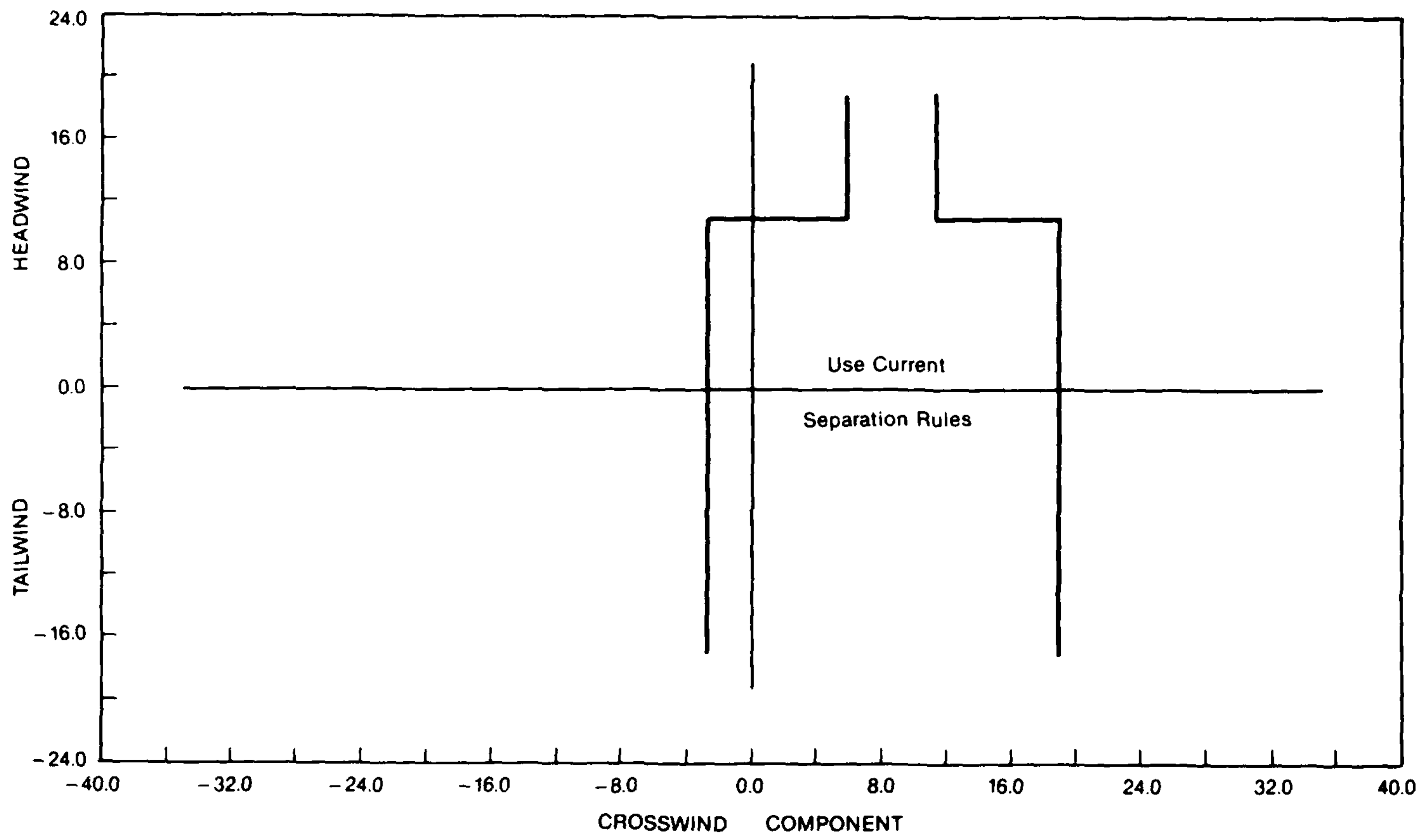


FIGURE 4
RUNWAY LAYOUT OF DENVER STAPLETON INTERNATIONAL AIRPORT



D = 1600 FT. S = 5800 FT. GS (2) = 3.0 DEG. (Small Behind Heavy)

FIGURE 5
DENVER WITH 3° GLIDE SLOPE

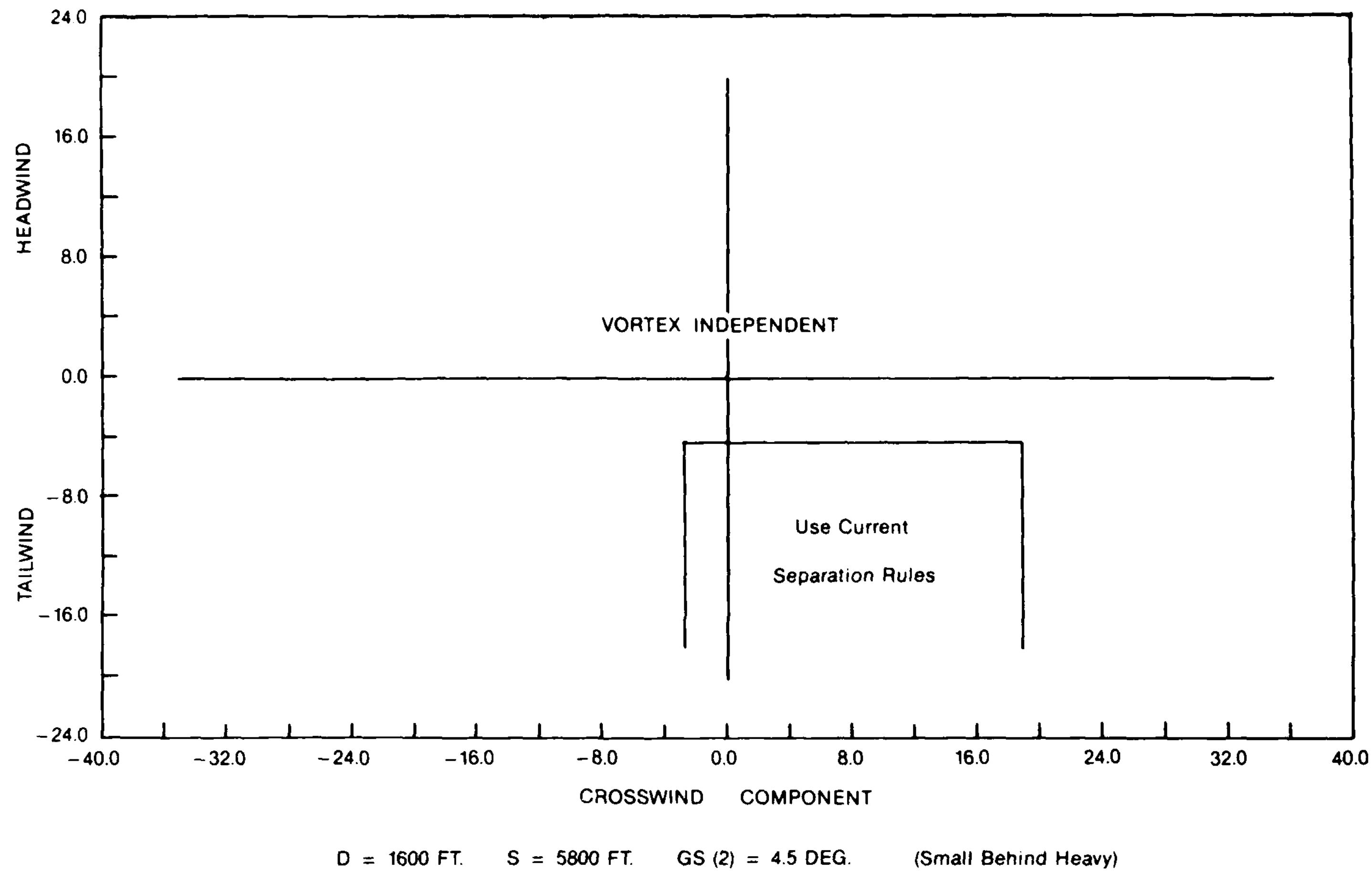


FIGURE 6
DENVER WITH 4.5° GLIDE SLOPE

5. OPERATIONAL FACTORS

There are a few remaining factors which must be addressed prior to implementing changes in separation rules. Among these are missed approach procedures, departure/arrival procedures, communications procedures, aircraft capabilities when using a steeper glide path, wind measurements, and lateral navigation errors. Some of these factors are independent of the airport configuration and will be discussed in this report. Others are site specific and depend on the runway geometry or require further investigation.

5.1 Missed Approach Procedures

Procedures must be developed to provide separation assurance in the event that the leading aircraft executes a missed approach.

In Figure 7, the shaded area represents the "footprint" of the vortex hazard in the event that the leading aircraft executes a missed approach and climbs while maintaining the localizer course, if the wind is from left to right. As the leading aircraft climbs, the footprint becomes narrower because it takes longer for the vortex to reach the ground. It is clear from the drawing that the wind conditions could be calculated which would place a hazardous vortex at or near the threshold of runway 2. In order to avoid such a hazard, it would be necessary to require simultaneous missed approaches and diverging courses. This implies that as soon as the leading aircraft declares a missed approach, the controller will require the trailing aircraft to begin a missed approach immediately. Since a missed approach by heavy aircraft is a rare event, the impact on the capacity benefits would be negligible if simultaneous missed approaches were required.

In the event that wind condition (4) (Table 1) exists when the leading aircraft executes its missed approach, the trailing aircraft can continue on its approach. This is because the vortex will be prevented from crossing the trailing aircraft's flight path, both in and out of ground effect.

5.2 Departure/Arrival Separations

Under current ATC separation rules, if an aircraft is departing from a runway on which another aircraft is intending to land, the other aircraft must be 2 nmi from the threshold when the first begins its takeoff roll. In particular, this applies to a departing heavy aircraft followed by a small arriving aircraft. This separation rule also applies to Denver Stapleton's operations on closely spaced parallel runways.

If the wind is from left to right, then a hazard may exist similar to that generated by a missed approach. Referring to Figure 7, imagine a heavy aircraft which begins its takeoff roll when a small aircraft is 2 nmi from the threshold of runway 1. The heavy aircraft will accelerate

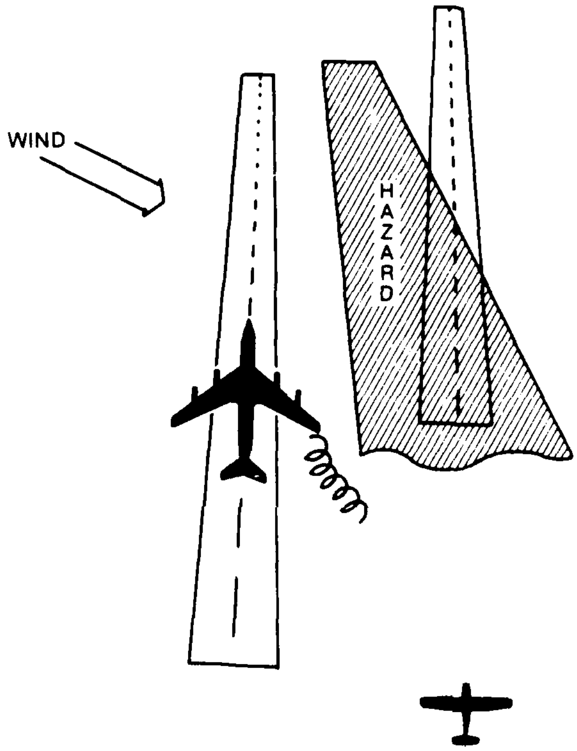


FIGURE 7
VORTEX HAZARD FOR MISSED APPROACHES AND DEPARTURE/ARRIVAL

and begin to rotate after about 30 seconds at a distance of at least 4000 feet from the threshold. When it rotates, it will begin generating a vortex similar to that of a landing aircraft. This vortex will then begin to drift toward the second runway. Meanwhile, the small aircraft, traveling at 90 kts will require a certain amount of time to travel the 2 nmi plus the distance S (in the case of Denver, S is 5800 feet).

The small aircraft traveling at 90 kts will be arriving at its threshold about 120 seconds after the heavy began its roll, depending on the actual separation. Consequently, the trailing aircraft would be in a hazardous area just as it crosses its threshold if the vortices can move the distance D (between the runways) during that time frame (from 30 to 170 seconds depending on the actual speeds, winds, stagger, etc.). From the parameters developed for this analysis, this is certainly a feasible condition. Since this analysis involves a worst-case approach it does not imply that the current situation is unsafe. It merely says that this analysis is unable to show that it is a safe procedure. Hopefully, this merely indicates that this analysis has been overly conservative. *However, the departure/arrival rules for closely spaced parallels should be reviewed to evaluate the effect of runway stagger on vortex hazards.*

5.3 Lateral Navigation Errors

A previous MITRE study [8] has reported that lateral navigation error can be several hundred feet, based on the International Civil Aviation Organization (ICAO) which published estimates of lateral navigation errors during Instrument Landing System (ILS) approaches to a single runway [9]. These results are given in Table 4. At a range of 4.21 nmi for example, the three sigma (3σ) deviation is 664 feet. If an allowance is made for this error by reducing the value of D in the wind equations, the effective distance between runways could become zero or negative if D is small. The only general solution to this problem is to increase the glide slope of runway 2 so that the crossover point disappears. Lateral navigation errors are about 50 feet within a mile of the threshold and the ground effect point will generally be within a mile of the threshold. When the trailing aircraft is in stage 2 it is above the path of the leading aircraft and lateral navigation errors have no effect on the analysis.

5.4 Remaining Questions

There are several unanswered questions which require further analysis. First there is the question of which aircraft are capable of flying the steeper glide slope. At a steeper glide slope, the descent rate (which is a function of ground speed) increases. For example, increasing the glide slope from 3 degrees to 4.5 degrees would change the descent rate from 634 feet per minute to 952 feet per minute for any aircraft flying at

TABLE 4
STANDARD DEVIATIONS OF AIRCRAFT DISPLACEMENT DURING AN ILS APPROACH

Category of ILS	Range (feet)	Lateral Displacement (feet)	Vertical Displacement* 3.0° GS (feet)	Vertical Displacement* 3.5° GS (feet)
CAT I	3937	53.8	19.03	22.3
	13780	117.8	44.6	52.2
	25590	221.5	89.9	104.7
CAT II Flight Director	3937	37.4	17.4	20.0
	13780	77.76	30.2	35.4
	25590	137.5	66.6	77.8
CAT III Auto Pilot	3937	37.4	14.4	16.7
	13780	55.1	20.71	24.0
	25590	97.44	40.7	47.6

Source: ICAO Collision Risk Model

* These values are well within the 0.7° error assumed in this analysis.

120 kts ground speed. It may require some flight testing to assess the capabilities of each aircraft type. Recent studies by FAA on the use of higher glide slopes with the Microwave Landing System (MLS) indicate that most jet aircraft must use less than 3.7 degree glide slope angles.

Second, if there are aircraft that are incapable of flying the higher glide slope angle, how will they be able to use the second runway in the event that the first ILS is inoperative? Unlike MLS, the ILS glide slope angle cannot be adjusted from the cockpit. The adjustment and recalibration takes time and therefore, is not something that would be done for short periods of time. An obvious, but perhaps costly, solution would be to install a backup 3 degree glide slope on the second runway. In the event it had to be used, the higher glide slope would be turned off and the 3 degree glide slope would be turned on. The obvious solution is to use the MLS with its capability to provide different glide slope angles on the same runway to MLS equipped aircraft.

Another area which requires further investigation is that of separation assurance on closely spaced parallel approaches. The localizer courses are less than 2500 feet apart and the longitudinal separation distance is 3 nmi or less. Can a radar controller determine from the radar alone that both aircraft are on the correct localizer and adequately separated? In the case of severe lateral navigation errors can the controller detect the error in time? It appears that some form of automatic detection system built into the software of a secondary surveillance system could address this problem. Other operational issues that must be addressed are the acceptability (to the pilots and controllers) of the procedures and how to determine when to start and stop the procedures when there is significant variability in the wind velocity.

Finally, there is the question of how to measure the wind velocities and directions at appropriate points during the approach. For example, with a 3 degree glide slope, wind measurements may be required as far as 9.5 nmi at an altitude of 3,000 feet for Denver. With a 4.5 degree glide slope or the use of a lower glide slope intercept altitude, the requirement for wind measuring at Denver reduces to less than 1.0 nmi from the threshold up to an altitude of 300 feet. Similar results can be expected at other sites. There are several pieces of equipment that can be used to measure wind velocities (e.g., anemometers, doppler acoustic radar, laser doppler velocimeter, and frequency modulated continuous wave radar). These would have to be evaluated to determine which is the best for a given configuration.

6. APPLYING THE ANALYSIS TO A SPECIFIC AIRPORT

The wind conditions that are required for safety are completely determined by the values of α_1, α_2, S and D. For most existing facilities the only parameter that can be controlled is α_2, the angle of the second runway's approach path. Consequently, the effects of increasing α_2 will be analyzed.

In general terms, the wind conditions required for vortex independence can best be described by drawing the V_h vs V_c diagram that was shown in the Denver example. There are four pictures that arise, corresponding to the classifications I, II, III, IV. These are shown in Figure 8. The numbers in parentheses refer to the equations which generated the boundaries of the safe region.

If α_2 is larger than some angle α_∞ (see Appendix A), the crossover point, CP, vanishes. If α_2 is larger than α_g, the ground effect point, GEP, is between the two thresholds, otherwise it is beyond the thresholds. Since α_∞ and α_g are constants which are independent of α_2, the analysis must consider cases which depend on which of the two is larger. If $\alpha_g > \alpha_\infty$, then if initially $\alpha_2 < \alpha_\infty$ the configurations will progress through II ($\alpha_2 < \alpha_\infty < \alpha_g$), IV ($\alpha_\infty < \alpha_2 < \alpha_g$) and III ($\alpha_\infty < \alpha_g < \alpha_2$) as α_2 increases. If $\alpha_\infty > \alpha_g$ and initially $\alpha_2 < \alpha_g$ the progression will be II ($\alpha_2 < \alpha_g < \alpha_\infty$), I ($\alpha_g < \alpha_2 < \alpha_\infty$) and III ($\alpha_g < \alpha_\infty < \alpha_2$) as α_2 increases (see Figure 8).

If the choice of α_2 results in classification II or I it is likely that the crosswind value determined by equation (4) will be the sole determinant of safety. Equation (4) determines the maximum value of the crosswind component that would prevent a vortex from being transported into the path of the smaller aircraft in the ground effect region. This is because it is a criterion which is easy to monitor, provides protection during all stages of the approach and during missed approaches, and is independent of the separation distance. In classification I, equation (1) may replace (4) in most situations because most landings are made into the wind (i.e., $V_h > 0$).

If the value of α_2 yields configurations III or IV, then the longitudinal wind component (6) or (7) provides a convenient measure of safety. Unfortunately, equations (6) and (7) do not provide protection during a missed approach, so that simultaneous missed approaches would be required if these conditions were the sole basis of vortex avoidance. The argument can be made that a missed approach by a heavy aircraft is a rare event so the impact on capacity of requiring simultaneous missed approaches is negligible.

Because most landings are made into the wind, it is desirable to increase α_2 so that classification III exists. In classification III there is no vortex hazard (except in the event of a missed approach) regardless of the diagonal separation and regardless of the crosswind component as long as there is a headwind.

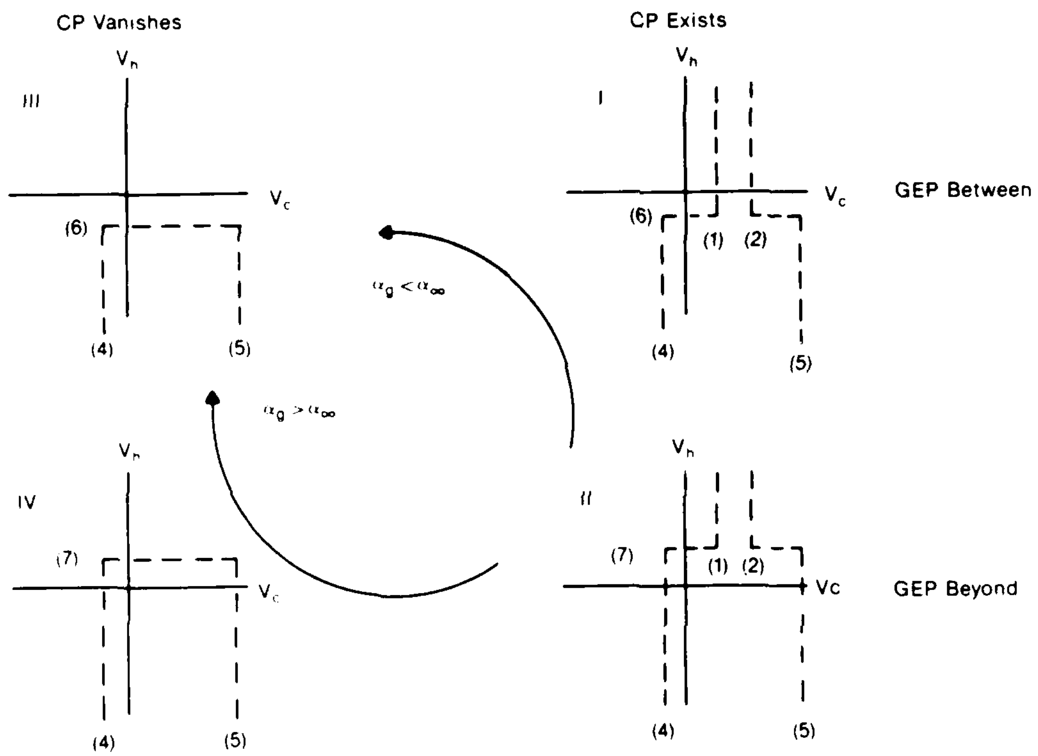


FIGURE 8
THE EFFECTS OF INCREASING α_2

In Figure 9 we show the relationship between S and α_2 which leads to classification III. Recall that classification III requires $\alpha_2 > \alpha_\infty$ and $\alpha_2 > \alpha_g$. It can be seen that in order to be in configuration III a value of S greater than 3800 feet is required when α_2 is less than 5.2 degrees.

This discussion is intended only to provide some insight on how to apply these results in a practical setting. Each runway pair would have to be evaluated separately. Unlike other capacity increasing concepts (e.g., independent parallel IFR operations), a detailed analysis of each site is required to determine if the geometry is suitable for implementation. There is no simple rule of thumb that can be used.

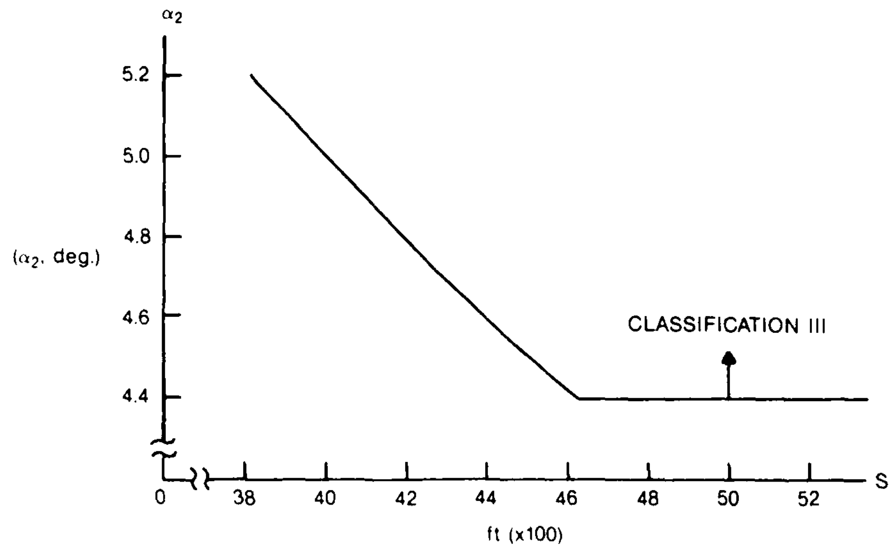


FIGURE 9
RELATIONSHIP BETWEEN S AND α_2 REQUIRED FOR CLASSIFICATION III

7. SUMMARY AND CONCLUSIONS

For parallel runways separated by less than 2,500 feet, the diagonal separations between aircraft on adjacent approaches are the same as if the aircraft were on the same approach. The problem of avoiding wake vortices has been a major hindrance to reducing diagonal separation distances on closely spaced parallel runways during instrument meteorological conditions. If diagonal separations could be reduced to 3 nmi or less, substantial increases in airport capacity during IFR conditions could be achieved.

Equipment that can lead to detection, and avoidance or alleviation of vortices has not yet completed development; in the interim, operational solutions to the problem are being considered. This analysis develops a procedure to determine whether diagonal separations can safely be reduced at specific sites. It involves a worst-case analysis using present, accepted knowledge of vortex behavior, along with aircraft performance, runway geometry and wind directions. Simple logic is employed to show that under certain meteorological conditions, vortices can be avoided at separation distances of 3 nmi or less with the leading heavy aircraft on one runway and the trailing small aircraft on the closely spaced parallel runway. The results are site dependent and care must be employed in making generalizations. The primary contribution is to show that significant results can be obtained if a site specific solution is sought rather than a global solution to the problem.

As an example to illustrate the use of the analysis, Denver Stapleton International is analyzed. When applied to runways 35L and 35R, it is shown that with the present 3 degree glide slope on 35R, separations can be reduced to 3 nmi or less whenever there is a 3 knot crosswind component from right to left (East to West). Further, if the glide slope angle for 35R could be increased to 3.7 degrees or greater, the vortex hazard would be eliminated as long as landing aircraft remain on the ILS approach and land into the wind. If the 3 degree glide slope was used, wind measurements would be required up to a distance of 9.5 nmi from the runway threshold up to 3000 feet AGL. If a 3.7 degree glide slope was used, wind measurements would only be required up to 1 nmi from the threshold and below 300 feet AGL. These preliminary results show great promise for the use of site specific analyses at other airports.

There are some remaining questions that require further analysis. The problem of vortex avoidance is greatly simplified if the glide slope on one of the runway can be increased to 4.4 degrees because an aircraft using that glide slope will remain above the vortex hazard during all but the last mile of its approach. However, some of the larger aircraft cannot fly an approach at such a steep angle, limiting the type of aircraft that can normally use the runway with the higher glide slope. In addition, this means that if a 4.4 degree glide slope were the only approach available on that runway, it would present a problem in the event that the 3 degree glide slope experienced an outage. There are ways to solve this problem (e.g., inclusion of MLS), but each needs further consideration with regard to operational requirements, equipage, and potential benefits and costs.

The second question concerns wind measurement devices. If the glide slope angle cannot be increased on the second runway, wind measurements may be required up to a distance of about 10 nmi from the runway thresholds. Further analysis is required to determine what kinds of wind measuring equipment can be used. There are operational benefits which result from using the shallower glide slope but these are offset by the cost of measuring winds at greater distances from the airport. A higher glide slope reduces the wind measuring requirements, but may prohibit some aircraft from using the approach.

In summary, use of a high angle glide slope (3.7 to 4.4 degrees) to a staggered touchdown point on a close parallel runway presents a feasible, safe, interim solution to the vortex problem at a number of airports. Its applicability depends upon two site-specific considerations:

1. Presence of a close parallel runway with appropriate length and/or stagger,

2. A sufficient population of aircraft that can routinely employ a higher glide slope,

and at all sites, the development of a simple, inexpensive wind measurement device that will provide a one axis (headwind/tailwind) profile over the last 1 nmi of the approach.

APPENDIX A

ANALYSIS AND DERIVATION OF WAKE VORTEX AVOIDANCE EQUATIONS

A.1 Motion of Wake Vortices

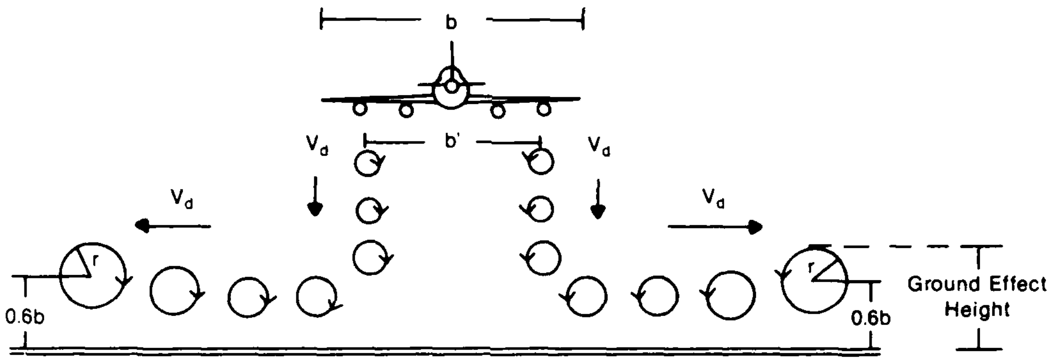
There have been many studies of the behavior of vortices dating back to the classic work by Sir Horace Lamb [5]. A summary of relevant results is contained in FAA-RD-77-23 [3] which is the primary reference for this analysis. The analysis in this appendix will begin with a discussion of the theory of vortex transport and each of the factors that affect the relative positions of the two flight paths.

Figure 10 illustrates the motion of wing tip vortices in and out of ground effect. The vortex pair is well-defined at a distance of approximately 2b behind the generating aircraft. The pair of vortices interact with each other inducing a downward velocity, V_d. The vortices descend at this rate which remains constant for t_s seconds, then decreases to zero at a distance of at most 1000 feet below the height at which they were generated. The rate of descent, V_d, is proportional to the strength of the circulation about the wing of the generating aircraft, Γ, and inversely proportional to its wingspan, b.

$$V_d = \frac{\Gamma}{2 \pi b'}$$

where, b' = Kb = initial separation of vortex pair. See Appendix B for values of K, t_s, b' and V_d.

When the pair of vortices descend to an elevation equal to about b/2, their interaction with the ground and with each other causes them to move in a horizontal motion that can be described analytically by assuming the existence of image vortices located an equal distance below the groundplane and analyzing the interaction of the four vortices. It is important to note that the motion of the vortices relative to the air mass is caused by the mutual interaction of the vortex pair rather than other forces such as gravity. In a simple model of vortex behavior, the horizontal velocity of each vortex is at most, V_d. This model neglects atmospheric instabilities and certain other factors involved in vortex decay. However, it is certain that V_d provides an upper bound on the horizontal velocity of the vortices as they begin to separate. The vortices remain at a constant altitude as they move in the horizontal plane for a certain distance, then they begin to rise to a height of about 0.8b' but not more than b [6].



V_d = Transport velocity of vortex in motionless air
b = Wingspan
r = Maximum radius of vortex
b' = Initial separation between vortices

FIGURE 10
THE MOTION OF WAKE VORTICES

This phenomenon is referred to as "vortex bounce". By the time that the vortex has begun to rise, the distance between the original pair is large enough to disregard the interaction effect. There is little published material concerning the motion of a vortex after the bouncing phenomenon has occurred. The vortex continues decaying after this time and by using the current FAA separation standards, it is possible to derive an upper bound on the life of a vortex hazard. The vortices also expand in size as they age achieving a radius of between 50 and 75 feet. This discussion has been condensed from Reference 3.

A.2 Relevant Aspects of Vortex Behavior

The purpose of the formulation is to specify what assumptions will be used to predict the movement of aircraft wake vortices. Each assumption is documented to show its source in the technical literature describing that aspect of vortex behavior, using the notation: [Reference, page].

A.2.1 Initial Formation Above Ground Effect:

1. Aircraft in landing configuration produces vortex pair [5]

2. Pair is separated by distance b' = 0.7b [3, 79]

3. Pair descends at velocity V_d [3, 78] [3, 47] [4, 4-27]

4. Velocity, V_d, remains constant for t_s secs [3, 84]

5. Upper and lower bounds for V_d (V_u and V_ℓ) are known [4, 4-27]

6. Radius of the vortex hazard increases with time and an upper bound, r, for the radius is known [4, 4-8] [3, 84]

7. Vortex pair descends to a distance of at most 1000 feet below the aircraft if aircraft is higher than 1000 feet + b/2 [3, 80], [3, 85], [7, 9] [7, 41]

8. Vortex may remain hazardous for 150 seconds based on 5 nmi separation for small behind heavy (FAA-0-7110.65B)

A.2.2 Vortex Motion In Ground Effect:

1. Ground effect begins at elevation b/2 AGL [3]

2. Horizontal velocity remains constant at or below V_d [3]

3. Vortex hazard exists from ground level to height equal to 1.6 times the initial half-separation of the vortices plus the hazard radius (0.8b' + r) [6, 3-33]

4. Vortex remains hazardous for 180 seconds based on 6 nmi separation for small behind heavy at threshold (FAA-0-7110.65B)

Considering all of these factors, there are a few relevant facts that will be used in this analysis.

1. The wingspan, b, of any heavy aircraft is less than 200 feet.

2. $V_{\ell} = 2$ ft/sec $V_u = 12.7$ ft/sec

3. $r < 75$ after 180 seconds.

The following analysis will require an upper bound on the height to which vortices bounce. Using the parameters 0.8b' feet for the maximum height of a vortex center and 75 feet for a vortex radius an estimate of 0.8 (0.7) (200) + 75 = 187 feet is obtained. By assuming that the radius of the vortex is less than 100 feet, the maximum height of a vortex in ground effect is taken to be 300 feet.

A.3 Runway Configuration Parameters

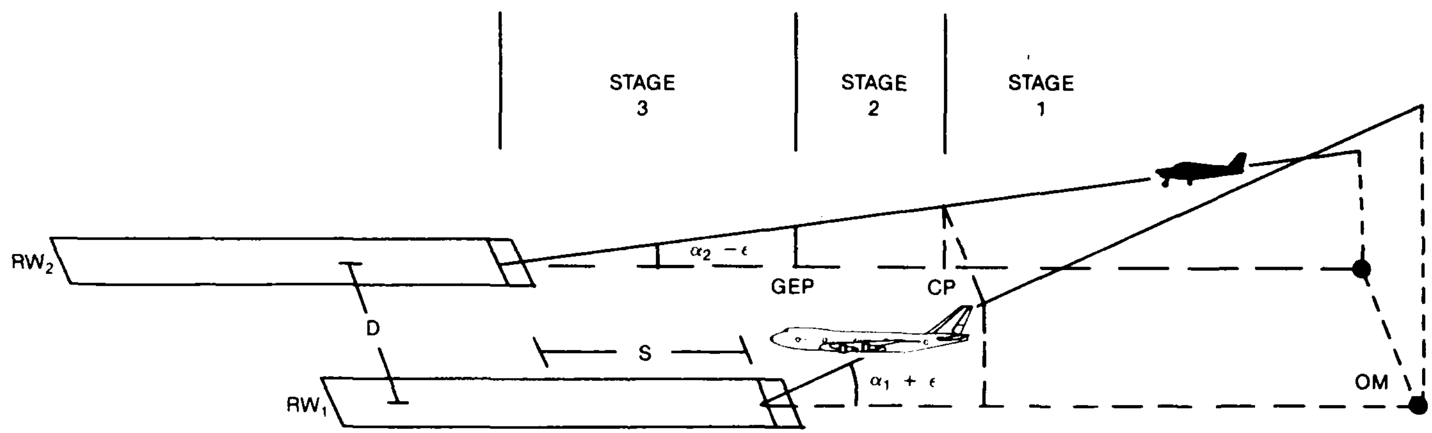
For purposes of analysis, the runway pair is assumed to be as shown in Figure 11. The runway which has its threshold closer to the outer marker (OM) will be called runway 1 (RW_1). The leading aircraft will be assumed to be a heavy aircraft on runway 1.

The OM will be located at a distance ℓ_1 from runway 1 and will be used for both runways. The centerlines of the runways are separated by a distance, D, which is less than 2500 feet. The thresholds are displaced or staggered by a distance, S, which can be any number greater than zero.

The angles of the glide slopes are α_1 and α_2 on runways 1 and 2, respectively. A maximum glide slope deviation of ε ($\varepsilon = 0.7°$ for ILS) is assumed which corresponds to both observed data and full-scale deflection of the glide slope indicator. In the worst case, the leading aircraft will fly a glide slope angle of $\alpha_1 + \varepsilon$ while the trailing aircraft flies an angle of $\alpha_2 - \varepsilon$. These paths are shown in Figure 11 and represent the upper and lower envelopes of the two flight paths.

The points labeled GEP and CP are defined as points on the runway 2 localizer. The GEP is located at a distance from the threshold where the height of the glide path envelope is 300 feet. The CP is located at the distance at which the altitudes of lower and upper envelopes just described are the same. These two points will be discussed in greater detail later in this appendix.

The approach path of the trailing aircraft is divided into 3 stages for the purposes of analysis. The crossover point, ground effect point and touchdown point divide the approach into stages 1, 2, 3 as shown in Figure 11.



D — Distance Between Runway Centerlines
S — Distance Between Thresholds
$\alpha_1 + \epsilon$ — Upper Limit for Leading Aircraft
$\alpha_2 - \epsilon$ — Lower Limit for Trailing Aircraft
CP — Crossover Point (May Not Exist)
GEP — Ground Effect Point (Between or Beyond Both Thresholds)

FIGURE 11
FLIGHT PATH GEOMETRY

A.3.1 Placement of Outer Marker

The signal from an OM radiates in a fan-shaped or lens-shaped pattern. At separation distances of less than 2500 feet it would be possible to detect the signal from both glide paths. Therefore it is necessary that the OMs of both approach paths be located at the same point. This may mean that one of the two aircraft may not intercept its glide slope at the OM. The location of the OM does not affect the following analysis.

A.3.2 Navigation Errors

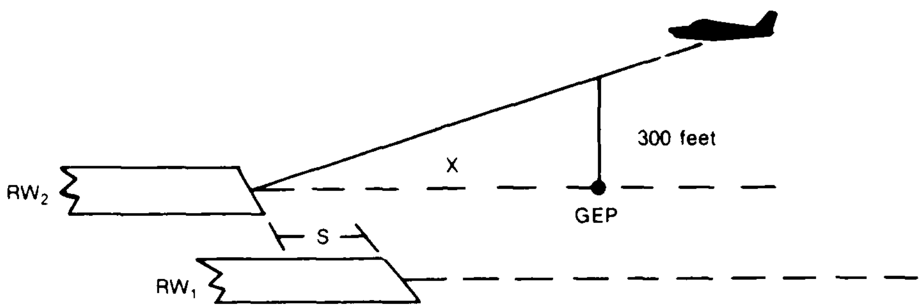
The ILS provides the pilot with lateral displacement (localizer) and vertical displacement (glide slope) by providing the corresponding angular displacement in analog form. An ILS approach being flown with the assistance of an auto-pilot will result in angular displacements of less than 0.35 degrees (half-scale deflection of the course deviation indicator). When the approach is flown manually, the Federal Aviation Regulations (FARs) require that the pilot declare a missed approach should full-scale deflection (0.7 degrees) occur. Therefore as a worst-case situation, it is assumed that the leading aircraft uses a glide path angle of $\alpha_1 + \varepsilon$ and the trailing aircraft uses $\alpha_2 - \varepsilon$, with $\varepsilon = 0.7$ degrees. Future guidance systems such as MLS may provide the aircraft with uniform course displacement measured in feet rather than degrees, which would allow better precision at greater distances from the threshold. With such a system it may be possible to ensure a vertical error of less than 150 feet. Once established on the localizer, the lateral navigation errors tend to be small and decrease as the aircraft approaches the threshold.

The point of touchdown is critical to the analysis because the aircraft ceases to generate vortices once it touches down. The desired touchdown point is approximately 1000 feet from the runway threshold but may vary in either direction by 300 feet. This dispersion of touchdown points will be considered to be negligible in this analysis because it requires only a minor correction in the value of S to account for this factor.

A.3.3 The Ground Effect Point

The ground effect point, GEP, is defined to be the point on the flight path of the trailing aircraft at which the aircraft is at an altitude of 300 feet AGL (see Figure 12). It occurs at a distance, X, from the threshold of runway 2, where

$$X = \frac{300}{\tan(\alpha_2 - \varepsilon)}$$



$$X = \frac{300}{\tan(\alpha_2 - \epsilon)} \text{ feet}$$

FIGURE 12
GROUND EFFECT POINT (GEP)

The GEP is defined to facilitate the analysis and has no operational significance. As will be shown later, the only significant factors are whether the GEP lies between or beyond both thresholds and the difference between the distances S and the GEP distance, X.

When the GEP is beyond both thresholds (as shown in Figure 12) the distance X - S will be called d_2. When the GEP is between the thresholds, the distance S - X will be called d_1. The analysis will treat each case separately.

A.3.4 Crossover Point

The crossover point, CP, is defined as the position on the lower envelope of the glide path of the trailing aircraft which occurs at a distance from the RW_2 threshold equal to

$$\frac{S \tan(\alpha_1 + \varepsilon)}{\tan(\alpha_1 + \varepsilon) - \tan(\alpha_2 - \varepsilon)},$$

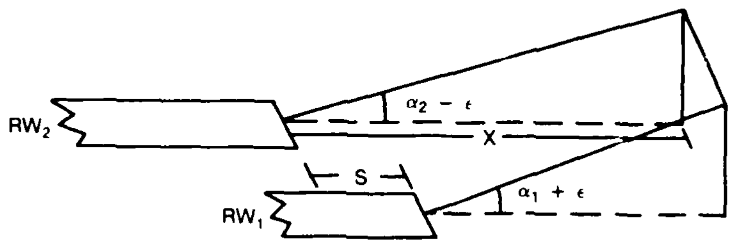
if at that distance the altitude of the glide path is at least 300 feet AGL (see Figure 13). Otherwise, the crossover point is defined to be the Ground Effect Point. It is the point on the RW_2 localizer at which the altitudes of the two flight path envelopes are the same. If $\alpha_2 - \varepsilon \geq \alpha_1 + \varepsilon$, the CP does not exist.

The significance of the CP is that prior to reaching this point, the trailing aircraft may be subject to a vortex hazard which was generated at a higher altitude. After passing the CP the flight path of the trailing aircraft will always be above the flight path of the leading aircraft. The CP is defined in order to make the analysis easier and has no operational significance. The CP may be moved towards or outside of the OM by either increasing the distance S or increasing α_2, or both. The effects of changing α_2 and S will be discussed later in this report.

A.3.5 Glide Path Angles

The trailing vortices descend below the glide path of the generating aircraft. Consequently, it is desirable to ensure that the trailing aircraft remains above the glide path of the leading aircraft. This can be accomplished by varying the glide slope angle on different runways and staggering the thresholds of the runways.

With the current ILS system the glide slope angle can be set to a specific value but cannot be readily changed. MLS will provide the capability of having different glide slope angles on the same runway with the capability of selecting the angle from the cockpit. In either case, it is necessary to know the interaction between the glide slope angles



$$(X - S)\tan(\alpha_1 + \epsilon) = X \tan(\alpha_2 - \epsilon)$$

$$X = \frac{S \tan(\alpha_1 + \epsilon)}{\tan(\alpha_1 + \epsilon) - \tan(\alpha_2 - \epsilon)}$$

FIGURE 13
CROSSOVER POINT (CP)

(α_1 and α_2), the crosswind component and the runway stagger distance, S. It can be seen in Figure 11 that the far runway (RW_2) should have a higher glide slope angle and be used for lighter aircraft as all of these factors tend to act together to place the trailing aircraft above the vortex hazard.

Increasing α_2 elevates the glide path of the trailing aircraft in relation to that of the leading aircraft. As α_2 increases, the CP moves away from the threshold until $\alpha_2 \geq \alpha_1 + 2\varepsilon$ at which point the CP vanishes. The GEP on the other hand, moves towards the threshold as α_2 increases.

A.3.6 Runway Stagger

Current Visual Flight Rules (VFR) practices effectively produce staggered runways because trailing light aircraft land beyond the touchdown point of heavier aircraft to avoid vortex hazards. This analysis will assume that the trailing aircraft uses the far runway (RW_2) because that places the touchdown point beyond the touchdown point of the leading aircraft.

Increasing the stagger distance, S, has a corresponding effect on the CP. As S increases, the CP moves away from the threshold, but the GEP remains at the same distance from the runway 2 threshold.

A.3.7 Classification of Runway Geometries

The goal of the analysis is to characterize the conditions under which the two runways become independent with respect to wake vortex separations. As will be shown in the analysis, there are only four classes to consider. The analysis differs depending on whether the crossover point exists or not, and whether the ground effect point is between or beyond the two thresholds. These conditions are completely determined by S and the relationship of α_2 to α_1.

There are two critical values of α_2, namely, α_g and α_∞ which are defined as:

$$\alpha_g = \varepsilon + \tan^{-1} \frac{300}{S} \qquad (\varepsilon = 0.7° \text{ for ILS})$$

$$\alpha_\infty = \alpha_1 + 2\varepsilon \qquad (2\varepsilon = 1.4° \text{ for ILS})$$

It can be seen that α_g has the property that if $\alpha_2 > \alpha_g$ the GEP is between the thresholds and if $\alpha_2 < \alpha_g$ the GEP is beyond the thresholds. If $\alpha_2 > \alpha_\infty$ the CP vanishes and if $\alpha_2 < \alpha_\infty$, the CP exists.

We define the four possible combinations as classifications I, II, III, and IV. The definitions are shown in Table 5.

TABLE 5
DEFINITIONS OF POSSIBLE CLASSIFICATIONS

Classification	CP	GEP	α_2
I	Exists	Between	$\alpha_g < \alpha_2 < \alpha_\infty$
II	Exists	Beyond	$\alpha_2 < \alpha_g$, $\alpha_2 < \alpha_\infty$
III	Vanishes	Between	$\alpha_g < \alpha_2$, $\alpha_\infty < \alpha_2$
IV	Vanishes	Beyond	$\alpha_\infty < \alpha_2 < \alpha_g$

A.3.8 Effects of Changing the Glide Slope Angle

As mentioned in section A.3.5, increasing α_2 moves the Crossover Point away from the threshold, moves the Ground Effect Point towards the threshold and raises the flight path of the trailing aircraft relative to that of the leading aircraft.

The geometry changes from one configuration to another as α_2 passes through the two critical values, α_g and α_∞. When α_2 equals α_∞ the flight paths are parallel, and when α_2 equals α_g the GEP is located at a distance S from the threshold of runway 2. Thus, when α_2 increases and passes through α_∞ the CP vanishes; and as α_2 passes through α_g, d_2 goes to zero and d_1 becomes positive, while the GEP moves from beyond to between the thresholds.

A.4 Longitudinal Separation Standards

Table 6 shows the current ATC separation standards for in-trail aircraft pairs. Of particular interest are the figures in the column under the heading "small". When a small aircraft is behind a heavy, it must maintain a 5 nmi separation on final approach and 6 nmi as the heavy crosses the threshold. Assuming that a small aircraft is traveling at an airspeed of 120 kts, the separation time, t_e, is 150 seconds. This fact is the justification for using 150 seconds as an upper bound on the lifetime of a vortex hazard when out of ground effect. The 6 nmi in-trail requirement implies that the lifetime of a hazardous vortex is 180 seconds in ground effect.

The notation "t_e" is used to represent the separation time between the two aircraft. These times are given in Table 6. Two values which will be used later are for a small aircraft trailing at 3 nmi separation (90 seconds) and for a large aircraft trailing at 5 nmi separation (138 seconds).

Airspeed rather than ground speed is used because both the vortex and the aircraft are being transported in the air mass. The value t_e is the time required by the aircraft to reach the vortex as a function of the separation distance and airspeed. If the winds are significantly different at different altitudes along the approach, only a minor adjustment in t_e is required. The effects of such differences will be ignored for the purposes of this analysis.

A.5 Analysis for Each of the Stages of the Flight Path of the Trailing Aircraft

The trailing aircraft will be in one of three (arbitrary) stages during the approach. "Stage 1" will refer to the portion of the glide path

TABLE 6
ATC SEPARATION STANDARDS FOR VORTEX AVOIDANCE

STANDARD IFR IN-TRAIL SEPARATION

TRAIL / LEAD	Small		Large		Heavy	
	nmi	(t_e)	nmi	(t_e)	nmi	(t_e)
Small	3	90	3	83	3	77
Large	(3) 4*	(90) 120*	3	83	3	77
Heavy	(5) 6*	(150) 180*	5	138	4	103

*Applies Only When Leading Aircraft is at Threshold

Class of Aircraft	Airspeed on Approach
Small Aircraft	120 kt
Large Aircraft	130 kt
Heavy Aircraft	140 kt

IMPLIES

For Small Behind Heavy Lifetime of Hazardous Vortex is

150 seconds Above Ground Effect

180 seconds In Ground Effect

of the aircraft beyond the CP, "stage 2" to the portion between the CP and the GEP and "stage 3" to the portion from the GEP to touchdown. One or more of the three methods of vortex avoidance (altitude, crosswind and harmless encounter) will be applied to each of the three stages in order to guarantee the safety of the trailing aircraft during the entire approach.

The following is a list of the assumptions that will be used:

1. Heavy aircraft is on RW_1
2. Trailing aircraft is on RW_2
3. Wind velocity is constant at all altitudes during approach
4. Touchdown dispersion of heavy aircraft is negligible
5. Deviation from glide slope does not exceed ε
6. Straight-in precision approaches only

There are two minor points to be mentioned before proceeding with the analysis. The CP may not exist under certain configurations. This occurs when $\alpha_2 \geq \alpha_1 + 2\varepsilon$. This is a desirable situation because it means that the trailing aircraft is always above the path of the leading aircraft and therefore out of the vortex hazard. When this case occurs, the aircraft will only experience stages 2 and 3 during its approach. In another case, the CP may occur at a point where the altitude of the trailing aircraft is equal to 300 feet. In this case, stage 2 does not exist because the CP and GEP coincide.

A.5.1 Stage 1, Beyond the CP

During this portion of the approach, as seen in Figure 14, the trailing aircraft may be separated by a vertical distance of less than 1000 feet below the glide path of the leading aircraft. The trailing aircraft will always be above 300 feet. The *crosswind* argument and the *harmless encounter* argument will be used to provide safety for the trailing aircraft. The following analysis applies only to those cases where stage 1 exists.

Referring to Figure 14, it is observed that the trailing aircraft may be anywhere within 1000 feet below the glide path of the leading aircraft. The crosswind component, V_c, is the only factor that could cause vortex transport toward the trailing aircraft. The strength of the crosswind required to prevent the vortex from moving into the glide path of the trailing aircraft can be computed. If t_a is the maximum lifetime of any vortex above ground effect, then a crosswind component, V_c, which satisfies:

$$\text{equation (1):} \quad V_c < \frac{D - \frac{b_1 + b_2}{2}}{t_a}$$

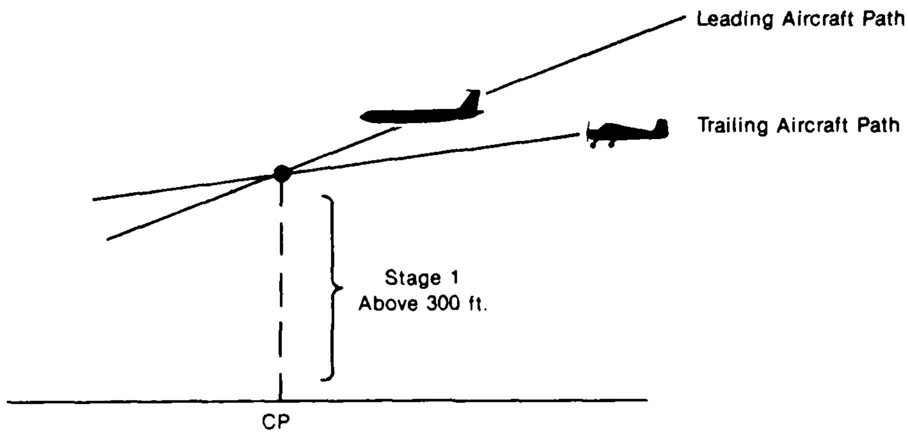


FIGURE 14
STAGE 1 GEOMETRY

will ensure that the inboard vortex of the leading aircraft does not reach the inboard wing of the trailing aircraft before time t_a. Hence this condition is safe for any separation distance because it ensures that the hazardous vortex never reaches the path of the trailing aircraft.

Another method to ensure safety is to require that the crosswind be strong enough to transport the outboard vortex beyond the outboard wing of the trailing aircraft before the aircraft reaches that point on its flight path. This condition is:

$$\text{equation (2):} \quad V_c > \frac{D + \frac{b_1 + b_2}{2}}{t_e},$$

where t_e is the time separation between the aircraft (see Table 6).

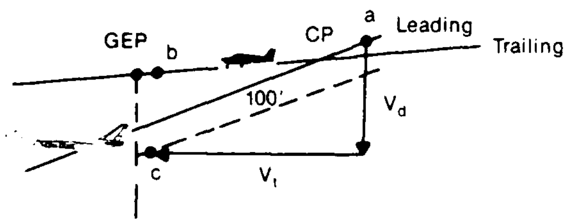
A.5.2 Stage 2, From the CP to the GEP

During Stage 2, the glide path of the trailing aircraft will be above the glide path of the leading aircraft. The *altitude* argument will be used to guarantee safety.

The altitude of the trailing aircraft will be greater than 300 feet AGL, and hence unaffected by vortices in ground effect. As seen in Figure 15, one way that an encounter could occur during stage 2 is for a vortex generated at some point "a" to be transported downward at speed V_d, laterally at V_c, and forward axially at V_t, so as to cross the glide path of the trailing aircraft at some point, b. A bound on the value of the tailwind V_t will be computed that will ensure that the vortex never rises above the flight path of the *leading* aircraft, hence will never reach the path of the trailing aircraft.

For a given tailwind component V_t, the vortex center will be transported from a to c. The hazard radius is less than 100 feet. The tailwind component, V_t, which is required to transport the vortex from a to c decreases as V_d decreases. The value of V_d ranges from 2 feet/second to 13 feet/second. Therefore, by using V_ℓ equal to 2 feet/second as a (conservative) lower bound on V_d, the required crosswind component is given by:

$$V_t = \frac{V_\ell t_e - 100}{t_e \tan(\alpha_1 + \varepsilon)}.$$



Lateral View

$$V_t < \frac{V_l \, t_e - 100}{t_e \tan(\alpha_1 + \epsilon)}$$

(3) $$V_t < 30.93 - \frac{1546}{t_e} \text{ ft/sec}$$

NOTE: Equations (1) and (2) also protect Stage 2

FIGURE 15
STAGE 2: SAFETY GUARANTEED BY THE ALTITUDE ARGUMENT

When V_t is less than

$$\frac{V_\ell t_e - 100}{t_e \tan(\alpha_1 + \varepsilon)},$$

the vortex hazard will never rise above the glide path of the *leading* aircraft. During stage 2 the glide path of the trailing aircraft is always above that of the leading aircraft, hence there is no possibility of a vortex encounter. The required condition is

$$\text{equation (3):} \quad V_t < \frac{V_\ell t_e - 100}{t_e \tan(\alpha_1 + \varepsilon)}.$$

It should be noted that conditions (1) and (2) also protect stage 2. Consequently, if any one of these conditions is true the trailing aircraft is protected during stage 2.

Another possibility for a hazardous vortex encounter might arise from a vortex traveling between points a and GEP, or such that the vortex enters ground effect. The previous value of V_d can no longer be used because of the ground effect and vortex bounce. This case can be evaluated by noting that once in ground effect, a vortex never rises above 300 feet AGL. The trailing aircraft is always above 300 feet AGL during stage 2 of the approach and therefore will be unaffected by these vortices.

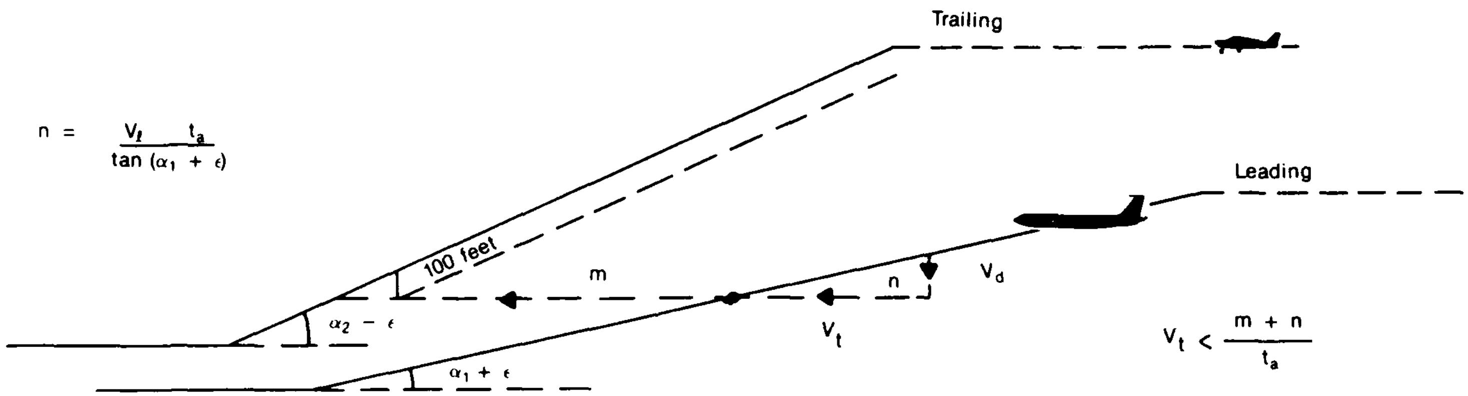
The previous analysis provides vortex avoidance from CP, the crossover point, to GEP, the ground effect point. When the crossover point does not exist or is so far from the runways that its existence is insignificant, the analysis changes.

In the first case, suppose that the CP does not exist. The objective is to provide safety during the approach up to the GEP. In Figure 16 it can be seen that the two diverging flight paths are closest at the GEP at an altitude of 300 feet AGL. The tailwind component, V_t, required to pose a hazard at this point is given by the equation:

$$V_t = \frac{S - \dfrac{100}{\tan(\alpha_2 - \varepsilon)} + \dfrac{300}{\tan(\alpha_1 + \varepsilon)} - \dfrac{300}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \frac{V_\ell}{\tan(\alpha_1 + \varepsilon)}.$$

$$m = S - \frac{100}{\tan(\alpha_2 - \epsilon)} + \frac{300}{\tan(\alpha_1 + \epsilon)} - \frac{300}{\tan(\alpha_2 - \epsilon)}$$

$$n = \frac{V_\ell \quad t_a}{\tan(\alpha_1 + \epsilon)}$$



$$V_t < \frac{m + n}{t_a}$$

FIGURE 16
ANALYSIS OF STAGE 2 WHEN CROSSOVER POINT DOES NOT EXIST

Equation (3a) applies only when the crossover point does not exist. Equation (3a):

$$V_t < \frac{S - \frac{100}{\tan(\alpha_2 - \varepsilon)} + \frac{300}{\tan(\alpha_1 + \varepsilon)} - \frac{300}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \frac{V_\ell}{\tan(\alpha_1 + \varepsilon)}.$$

The second case (Figure 17) occurs when the crossover point is far enough out so as to be insignificant. It is assumed that the two aircraft are separated by sufficient altitude (at least 1000 feet) prior to intercepting the glide slope. The leading aircraft will be at altitude A_1 (AGL) and the trailing aircraft will be at altitude $A_2 > A_1$. The point at which the leading aircraft intercepts its glide slope (point a in Figure 17) is at a distance:

$$S + \frac{A_1}{\tan(\alpha_1 + \varepsilon)}$$

from the runway 2 threshold. The trailing aircraft descends to this altitude (point b in Figure 17) at a distance:

$$\frac{A_1}{\tan(\alpha_2 - \varepsilon)}$$

from its threshold.

Since the paths only intersect at the crossover point (assumed to be far away from the OM), the point at which they are closest is at the altitude A_1. The bound on the tailwind required to prevent the transport of a vortex generated at point a in Figure 17 to the point b, is given by equation (3b):

$$V_t < \frac{S - \frac{100}{\tan(\alpha_2 - \varepsilon)} + \frac{A_1}{\tan(\alpha_1 + \varepsilon)} - \frac{A_1}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \frac{V_\ell}{\tan(\alpha_1 + \varepsilon)}.$$

Both of these equations are less restrictive than that implied by equation (3). That implies that in a practical setting, if equation 3 holds, it is not necessary to verify equations 3a and 3b.

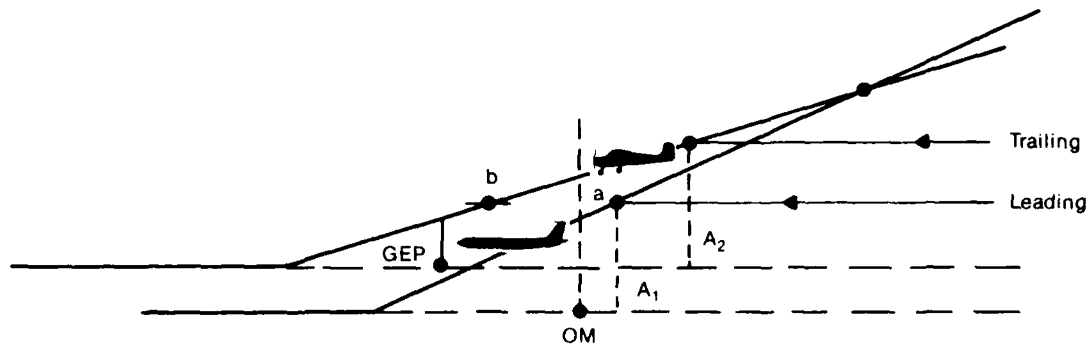


FIGURE 17
STAGE 2: WHEN CROSSOVER POINT IS FAR BEYOND OUTER MARKER

A.5.3 Stage 3, From GEP to Touchdown

During this portion of the approach, it is possible that vortices, which are transported in-ground effect, could cross the approach path of the trailing aircraft. The trailing aircraft will be at an altitude of less than 300 feet. This portion of the analysis will be further divided into the case where the GEP is between the thresholds of both runways (Case 1) and the case where the GEP is beyond both thresholds (Case 2). The *crosswind* and *harmless encounter* arguments will be used to guarantee safety.

As seen in Figure 18, if the GEP occurs between the two thresholds, the only way the trailing aircraft could encounter a vortex is in the presence of a tailwind and crosswind strong enough to transport the vortex towards the RW_2 threshold and beyond the GEP.

The inboard vortex is transported laterally at a velocity of at most $V_u + V_c$ so the strength of V_c required to pose a hazard can be computed from Figure 18. In-ground effect, the lifetime of a vortex hazard is t_g. The inboard vortex of the leading aircraft can be prevented from moving across the flight path before time t_g if:

$$V_u + V_c < \frac{D - \frac{b_1 + b_2}{2}}{t_g}$$

This leads to:

equation (4): $$V_c < \frac{D - \frac{b_1 + b_2}{2}}{t_g} - V_u$$

The stage can also be protected if the crosswind is strong enough to blow the vortex beyond the outboard wing of the trailing aircraft before time t_e. This leads to:

equation (5): $$V_c > \frac{D + \frac{b_1 + b_2}{2}}{t_e} - V_u$$

Safety can also be ensured by requiring that the tailwind, V_t, not be strong enough to transport the vortex a distance d_1 in t_g seconds. This yields the condition,

equation (6): $$V_t < \frac{d_1}{t_g}$$

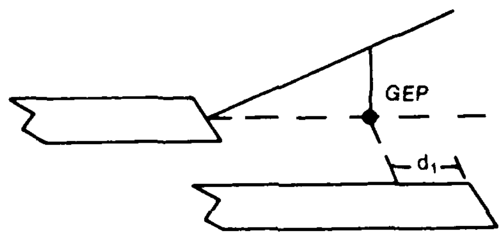


FIGURE 18
STAGE 3, CASE 1 ($d_1 > 0$)

In the second case we consider the GEP to be beyond both thresholds as shown in Figure 19. The distance d_2 is the distance between the GEP and the threshold of runway 1. Equations (4) and (5) developed for case 1 also apply to this case.

Another condition for safe operations would be to require the headwind to be strong enough to move the vortex out of the path of the trailing aircraft.

This condition can be summarized as:

equation (7): $$V_h > \frac{d_2}{t_e}.$$

A.5.4 Summary of Analysis

The analysis that has been developed in section A.5 can be applied to any airport to compute the required wind conditions and vortex avoidance procedures. Before applying the analysis to a specific example the results are summarized.

In Table 7 equations (1) through (7) are summarized showing the stages that they protect. Equations (8) and (9) show wind conditions which were derived by considering the simultaneous effects of lateral and longitudinal wind. The wind conditions implied by equations (8) and (9) are difficult to measure so they will not be considered in the analysis, but are given for completeness.

In Figure 20, the wind conditions and safe regions are presented in a form to show their relationship. In order to ensure a safe approach it is necessary that each of the stages that exist be protected. Hence, using Figure 20 it is easy to see which subsets of conditions can be used to ensure safety. These conditions are given in Table 8 for the four possible classifications described in section 6, Figure 8. The analysis technique is demonstrated by applying it to Denver Stapleton International.

A.6 An Example: Denver Stapleton International Airport

Denver Stapleton International Airport is a good example because it is an existing facility that has closely spaced parallel runways and a large threshold stagger. In the following calculations, it is shown that under its current configuration, separation distances can be reduced with the presence of a light crosswind. If the glide slope angle of the Runway 35R is increased to 4.5 degrees, the two runways can be vortex independent regardless of the crosswind component as long as there is a headwind component.

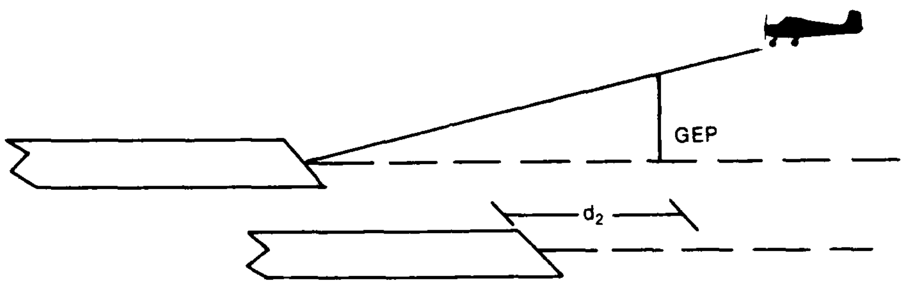
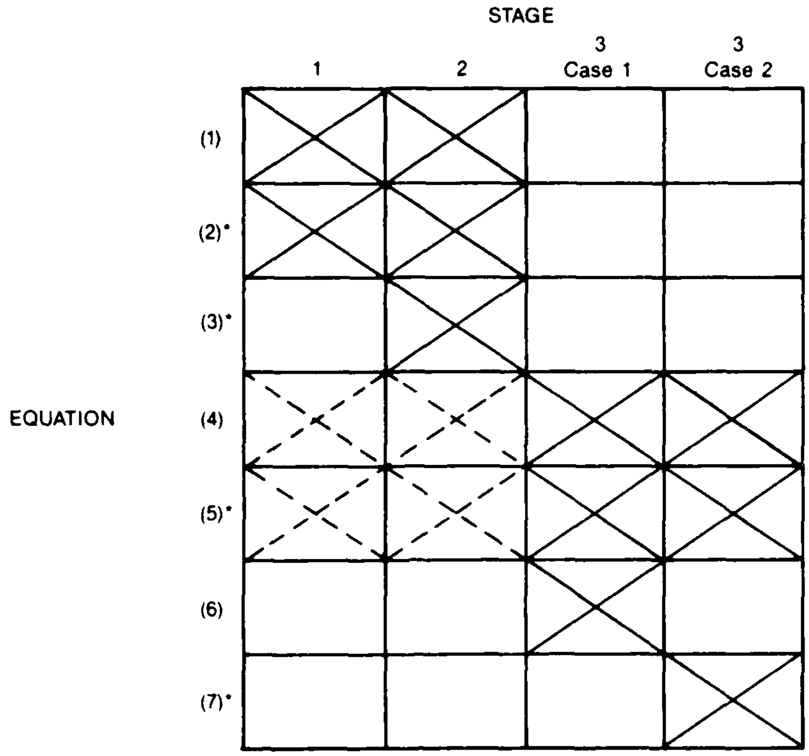


FIGURE 19
STAGE 3, CASE 2 ($d_2 > 0$)

TABLE 7
SUMMARY OF WIND CONDITIONS FOR VORTEX AVOIDANCE

	STAGE PROTECTED
(1) $V_c < \dfrac{D - \dfrac{b_1 + b_2}{2}}{t_a}$	1, 2
(2) $V_c > \dfrac{D + \dfrac{b_1 + b_2}{2}}{t_e}$	1, 2
(3) $V_t < \dfrac{V_\ell t_e - 100}{\tan(\alpha_1 + \varepsilon)\, t_e}$	2 CP exists
(3a) $V_t < \dfrac{S - \dfrac{100}{\tan(\alpha_2 - \varepsilon)} + \dfrac{300}{\tan(\alpha_1 + \varepsilon)} - \dfrac{300}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \dfrac{V_\ell}{\tan(\alpha_1 + \varepsilon)}$	2 (CP does not exist)
(3b) $V_t < \dfrac{S - \dfrac{100}{\tan(\alpha_2 - \varepsilon)} + \dfrac{A_1}{\tan(\alpha_1 + \varepsilon)} - \dfrac{A_1}{\tan(\alpha_2 - \varepsilon)}}{t_a} + \dfrac{V_\ell}{\tan(\alpha_1 + \varepsilon)}$	2 (CP exists but is operationally not critical)
(4) $V_c < \dfrac{D - \dfrac{b_1 + b_2}{2}}{t_g} - V_u$	3 (Implies 1, 2)
(5) $V_c > \dfrac{D + \dfrac{b_1 + b_2}{2}}{t_e} - V_u$	3 (Implies 1, 2)
(6) $V_t < \dfrac{d_1}{t_g}$	3 (CASE 1)
(7) $V_h > \dfrac{d_2}{t_e}$	3 (CASE 2)
(8) $(V_u + V_c)^2 + V_t^2 < \dfrac{\left(D - \dfrac{b_1 + b_2}{2}\right)^2 + d_1^2}{t_g^2}$	3 (CASE 1)
(9) $(V_c - V_u)^2 + V_h^2 > \dfrac{\left(D + \dfrac{b_1 + b_2}{2}\right)^2 + d_2^2}{t_e^2}$	3 (CASE 2)

(Note: Equations (8) and (9) are second Order Refinements that are Difficult to Implement)



Equation (4) Implies Equation (1)
(5) Implies Equation (2)

*Minimum Separation Distance is Required to Compute t_e.
— Wind Requirements are More Restrictive for Lower Values of t_e
(e.g., Large Behind Heavy at 3 nmi Implies t_e = 83 Secs)

*Note: Equation (3) Includes Equations (3a) and (3b) Depending on the Location of the Crossover Point.

FIGURE 20
STAGES PROTECTED BY EACH EQUATION

TABLE 8
WIND CONDITIONS REQUIRED FOR EACH CLASSIFICATION

CLASSIFICATION	CP	GEP	EQUATIONS
I	Exists	Between	(4) or (5) or (1 and 6) or (2 and 6)
II	Exists	Beyond	(4) or (5) or (1 and 7) or (2 and 7)
III	Vanishes	Between	(4) or (5) or (1 and 6) or (2 and 6) or (3 and 6)
IV	Vanishes	Beyond	(4) or (5) or (1 and 7) or (2 and 7) or (3 and 7)

Figure 4 represents a layout of Denver Stapleton International Airport. The essential parameters for Runway 35R and 35L are extracted and shown in Figure 21.

The runway centerlines are separated by 1600 feet and the thresholds are displaced 5800 feet. Currently the two glide slope angles are 3 degrees. This implies that the geometry fits classification II (α_∞ = 4.4 degrees and α_g = 3.66 degrees). If the value of α_2 were to be increased above 4.4 degrees the geometry would become classification III. In this example we will consider two cases, with α_2 = 3 degrees and α_2 = 4.5 degrees.

The speeds implied by equations (1) through (7) are given in Table 9. The calculations assume a small aircraft behind a heavy at 3 nmi with no wind shear and no lateral navigation errors. The conditions for safety are represented by Figures 22 and 23.

In Figure 22, equation (4) implies that there is no hazard posed by wake vortices as long as the crosswind component is from right to left and at least 2.7 kts. Because equation (4) does not depend on a separation distance, it can be concluded that a 2.7 kt crosswind will make Runways 35R and 35L vortex independent for all diagonal separations. Other wind conditions also imply safety, but condition (4) is the easiest to implement.

If α_2 is increased to 4.5 degrees, the results are equally satisfying. As seen in Figure 23, the approach is safe in the presence of a headwind regardless of the separation distance and regardless of the crosswind. Since most landings are made into the wind (i.e., with a headwind component) this result will eliminate the vortex hazard for almost all situations. Furthermore, as long as equation 3(b) is true, wind information is needed only in the area from the threshold to the GEP which is less than a mile from the threshold and within the airport boundaries. Equation 3(b) is true whenever the aircraft are landing with a tailwind of less than 35 kts (which is operationally always true).

If a large aircraft is following the heavy the values of t_a, t_e, t_g, and b_2 change. The net effect is to shift the bottle-shaped region in Figures 22 and 23 to the right as shown by the dashed line. Note that equations (4) and (6) still imply safety for all aircraft under classifications II and III, respectively.

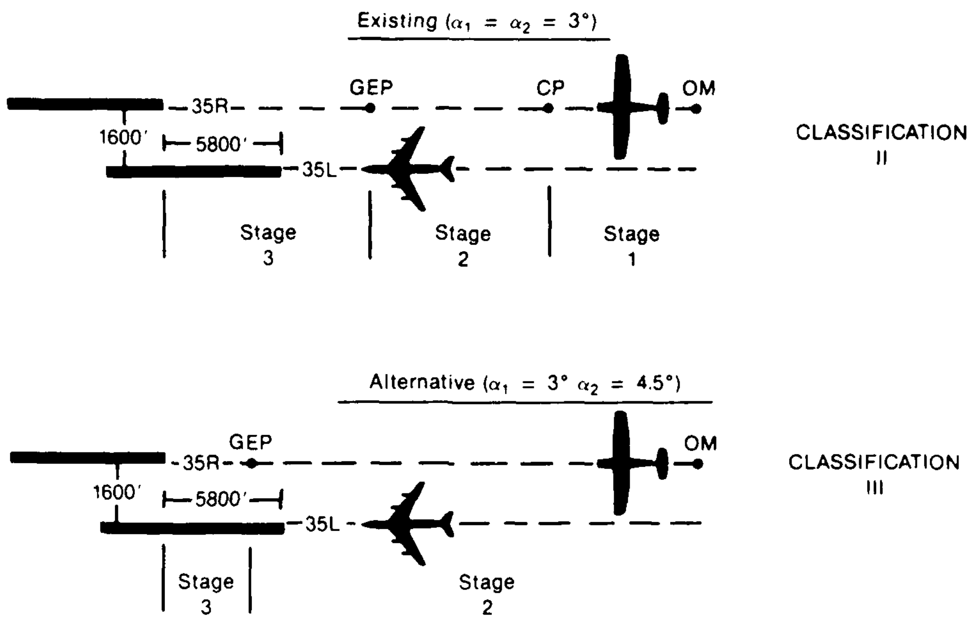


FIGURE 21
RUNWAY GEOMETRY AT DENVER

TABLE 9
WIND SPEEDS FOR DENVER ANALYSIS

	$\alpha_2 = 3°$		$\alpha_2 = 4.5°$	
EQUATION	FEET(SECONDS)	kts	FEET(SECONDS)	kts
(1)	1480(150)	5.85	1480(150)	5.85
(2)	1720(90)	11.3	1720(90)	11.3
(3)	80(5.82)	8.11	N/A	N/A
(3a)	N/A	N/A	(60.37)	35.77
(4)	1480(180)	-2.7	1480(180)	-2.7
(5)	1720(90)	18.85	1720(90)	18.85
(6)	N/A	N/A	1283(180)	4.22
(7)	1670(90)	11	N/A	N/A

NOTE: Equations (2), (5) and (7) assume 3 nmi separation.

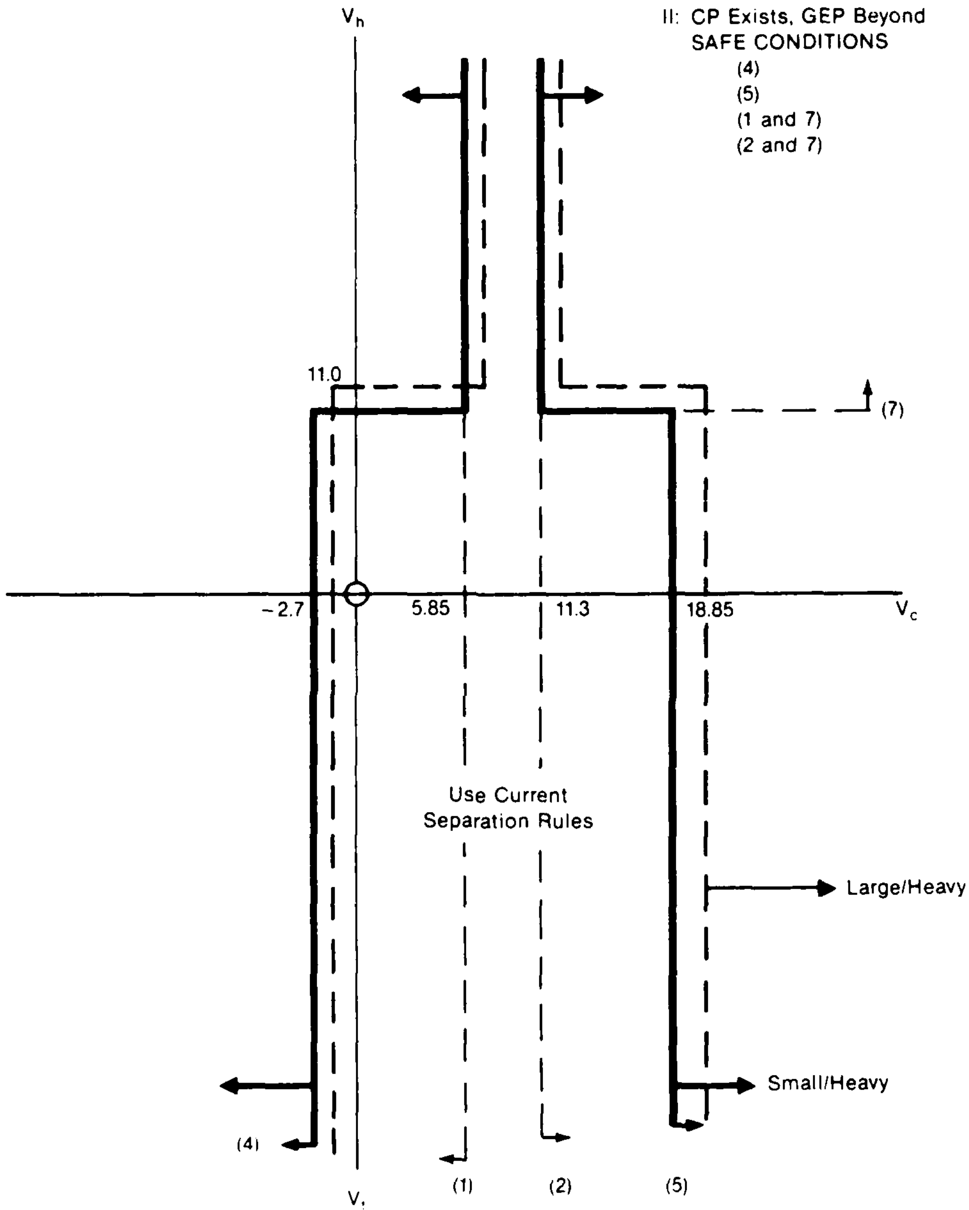


FIGURE 22
DENVER (EXISTING, $\alpha_2 = \alpha_1 = 3°$)

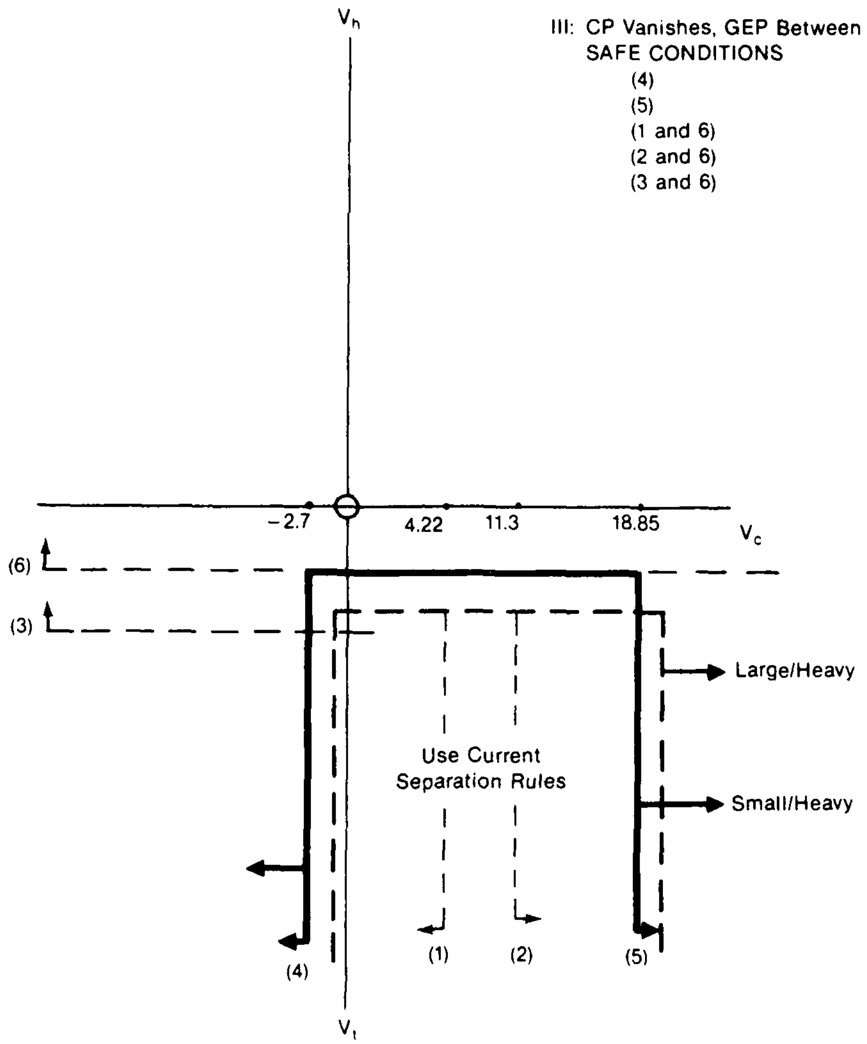


FIGURE 23
DENVER (α_2 = 4.5)

A.7 Extensions of Concept to Achieve Lower Glide Slope Angles

When there is sufficient stagger between the thresholds, the crossover point, CP, moves farther away from the airport. The CP occurs at the point where the upper envelope of the lower glide slope meets the lower envelope of the higher glide slope. In Figure 13, the distance from threshold 2 at which this occurs is calculated.

$$\text{Let } Q = \frac{S \tan(\alpha_2 - \varepsilon)}{\tan(\alpha_1 + \varepsilon) - \tan(\alpha_2 - \varepsilon)},$$

be this distance measured from the runway 1 threshold to the CP. Then the altitude at which the two envelope lines intersect is given by the equation

$$A = Q \tan(\alpha_1 + \varepsilon) = (S + Q) \tan(\alpha_2 - \varepsilon).$$

If the heavier aircraft on the lower glide slope can be forced to remain below this altitude, it will never be above the lighter aircraft and thus will never produce a vortex hazard above the ground effect point. As seen in Figure 24, the obvious solution is to require that the heavier aircraft use a glide slope intercept altitude that is below the altitude, A, calculated above. Simultaneously, the higher aircraft must use a glide slope intercept altitude which is greater than A. For ease of illustration and implementation, it is sufficient to assume that the lighter aircraft will intercept its glide slope at an altitude that is 500 feet higher than the heavier aircraft. For safety, noise, and other reasons, the glide slope intercept altitude must be at least 1,500 feet AGL. Consequently, the analysis must be able to calculate the appropriate value of α_2 that will produce a value of A equal to 1,500 feet for given values of S and α_1. Solving for α_2 we obtain:

$$\alpha_2 = \varepsilon + \tan^{-1}\left(\frac{A \tan(\alpha_1 + \varepsilon)}{S \tan(\alpha_1 + \varepsilon) + A}\right)$$

Consequently, if the intercept altitude of the heavier aircraft on runway 1 is A or lower, and that of the lighter aircraft is 500 feet or more above it, the heavier aircraft will always be below the lighter aircraft if the glide slope angle on runway 2 is at least α_2.

In the case of Denver, $\varepsilon = 0.7$, $\alpha_1 = 3.0$, $S = 5{,}800$. Using $A = 1{,}500$ we obtain $\alpha_2 = 3.7$ degrees. In Table 10, the values of α_2 are calculated for selected values of threshold stagger, S, and different glide slope intercept altitudes. The numbers in the table are values of α_2 associated with the corresponding values of S and glide slope intercept altitude.

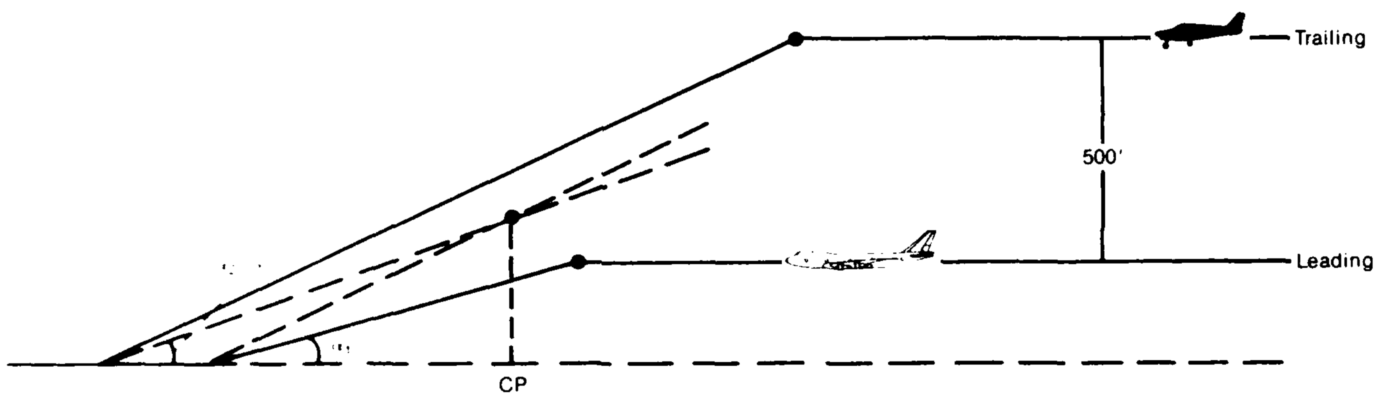


FIGURE 24
USE OF DIFFERENT GLIDE SLOPE INTERCEPT ALTITUDES

TABLE 10
RUNWAY 2 GLIDE SLOPE ANGLES (α_2)

Stagger (ft)	Intercept Altitude (ft) 1500	2000	2500
0	4.4	4.4	4.4
1,000	4.2	4.3	4.3
2,000	4.1	4.2	4.2
3,000	4.0	4.1	4.1
4,000	3.9	4.0	4.1
5,000	3.7	3.9	4.0
6,000	3.6	3.8	3.9
7,000	3.5	3.7	3.8
10,000	3.3	3.5	3.6

The advantage of the use of lower intercept altitudes is that with these (lower) values of α_2, wind measurement equipment is only required below 300 feet within a mile of the runway 2 threshold. This means that a system of ground based anemometers will probably suffice. The lower glide slope angles mean that more aircraft can use the second runway.

APPENDIX B

INITIAL VORTEX PARAMETERS[1]

Aircraft	Config.	Airspeed	K	b'	V_d	t_s
		(m/sec)		(m)	(m/sec)	(sec)
B-747	Takeoff	83	0.74	44.2	1.8	195
	Holding	113	0.80	47.8	1.3	282
b = 59.7 m	Landing	75	0.70	41.8	2.1	153
L-1011	Takeoff	85	0.78	36.8	1.7	169
	Approach	81	0.74	35.0	2.0	134
b = 47.2 m	Landing	73	0.71	33.5	2.5	104
DC-10	Takeoff	78	0.63	29.8	2.8	83
	Approach	74	0.62	29.3	2.7	85
b = 47.2 m	Landing	70	0.62	29.3	2.9	78
B-727	Takeoff	66	0.70	23.0	2.4	77
	Holding	105	0.67	22.1	1.6	112
b = 32.9 m	Landing	64	0.67	22.1	2.6	67

1 Taken from Reference [1].

APPENDIX C

VALUES OF V_d FOR SELECTED AIRCRAFT[1]

Aircraft Model	Maximum Landing Weight (lb)	Initial Descent Velocity V_d (ft/sec)	σ (ft/sec)
B-707/120B	190,000	5.3(5.2*)	1.8*
B-707/320B	247,000	5.5	1.8
B-727/100	142,500	6.6	1.9
B-737/100	101,000	6.5	1.9
B-747/200B	564,000	6.8(6.3*)	1.9*
DC-8/20	199,500	4.9	1.8
DC-8/62	240,000	5.7	1.8
DC-9/20	93,400	6.2	1.9
DC-10/30	403,000	7.0	1.9
L-1011/200	368,000	7.0	1.9
PA-28-180	3,600	4.0	1.7
Learjet-25	13,300	7.5	1.9

* Measured Values.
1 Taken from Reference [2].

APPENDIX D

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APPENDIX E

SUMMARY OF SYMBOLS

α_i	Glide Slope Angle of Runway i (i = 1, 2)
ε	Maximum Vertical Navigation Error on Glide Slope
Γ	Circulation About the Wing of an Airfoil
A	Altitude (AGL) of CP
b	Wingspan of Aircraft
b'	Initial Separation of Tip Vortices
D	Distance Between Runway Centerlines
d_1	Distance Between GEP to RW_1 Threshold When the GEP is Between the Two Thresholds
d_2	Distance Between GEP to RW_1 Threshold When the GEP is Beyond Both Thresholds
ℓ_i	Distance from RW_i to OM
L	Maximum Length of Time After the Generating Aircraft Has Passed that a Vortex Remains Hazardous
Q	Distance from RW_1 Threshold to CP
RW_i	Runway i. i = 1 is Defined so that Runway 1 has its Threshold Closer to the OM (i.e., $\ell_1 = \ell_2 - S$)
S	Distance Between Two Thresholds (Also Called Runway Stagger)
t_a	Lifetime in Seconds of Vortex Hazard Above Ground Effect Height
t_e	Separation Between Leading and Trailing Aircraft Measured in Seconds
t_g	Lifetime in Seconds of Vortex Hazard In-Ground Effect
V_1	Airspeed Component in Direction of Flight Path of Leading Aircraft

V_2	Airspeed Component in Direction of Flight Path of Trailing Aircraft
V_c	Crosswind Velocity Component in + Y Direction
v_d	Induced Velocity of Vortex
V_u	Upperbound on Initial Descent Velocity of Vortex
V_ℓ	Lowerbound on Initial Descent Velocity of Vortex
V_h	Headwind Component
V_t	Tailwind Component in -X Direction
X	Distance from Runway Threshold Along the Localizer Course of the Trailing Aircraft
X_{min}	Minimum Separation in nmi Between Leading and Trailing Aircraft
Y	Lateral Distance from the Leading Aircraft Towards Trailing Aircraft
Z	Vertical Distance Below the Leading Aircraft

APPENDIX F

ACRONYMS

AGL	Above Ground Level
ATC	Air Traffic Control
CP	Crossover Point
DEG	Degree
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
ft	Feet
GEP	Ground Effect Point
GS	Glide Slope
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
kts	Knots
m	Meter
MLS	Microwave Landing System
nmi	Nautical Mile
OM	Outer Marker
secs	Seconds
tan	Tangent
VAR	Magnetic Variation
VFR	Visual Flight Rules

END

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